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Life Cycle based Dynamic Assessment Coupled with Multiple Criteria Decision Analysis: A Case Study of Determining an Optimal Building Insulation Level

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Abstract:

This work looks at coupling Life cycle assessment (LCA) with a dynamic inventory and multiple criteria decision analysis (MCDA) to improve the validity and reliability of single score results for complex systems. This is done using the case study of a representative Danish single family home over the service life of the building. This case study uses both the established and the coupled MCDA assessment methods to quantify and assess the balance of impacts between the production of mineral wool insulation versus the production of space heat. The use of TOPSIS method for calculating single scores is proposed as an alternative to the ReCiPe single score impact assessment method. Based on the single score impact values obtained from both

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of these methods, various insulation levels are ranked to determine an ideal insulation level and gauge the effectiveness of environmental impact reduction measures in current Danish building regulations. Using a comparison of the results from the two methods, a preferred choice of impact assessment method is determined. The findings show that if the midpoint impacts for a particular scenario are strongly correlated with a climate change impact indicator, it does not matter which impact assessment is applied. However, for the scenarios where other impact categories vary inversely or independently from the climate change impact indicator, such as with renewable energy production, there is need for a more unconventional method, such as the TOPSIS method, for calculating single score impacts.

Keywords: Life cycle assessment; building material; mineral wool insulation; multiple criteria decision making

1.0 Introduction

In Denmark, there are nearly 1.2 million single family detached houses (SFDH) making up approximately 45% of all dwelling units (Klintefelt 2016). These houses use over 76 petajoules of energy annually, and approximately 63% use district heating, with district heating accounting for nearly 37% of total residential energy use (Energistyrelsen 2014). While these numbers do not represent a huge global impact potential, in other countries the market is much larger and SFDH can make up an even larger proportion of the national building stock, such as in the US, where SFDH make up over 63% of all dwelling units (EIA 2009). Overall, the heating of houses, in particular single family homes, accounts for major global health, environmental and economic impacts. While space heating is necessary in most all houses, insulation also plays a key role in keeping a house warm by minimizing heat losses. This poses the challenge of determining an optimized balance between the provision of heat and application of insulation to achieve a defined level of livable condition (around 20^{o} C).

Over the last several decades, regulations have shifted toward requiring much higher levels of insulation (Papadopoulos 2005). The result of this increased usage of higher levels of insulation has led to study of the emergy impacts of increased insulation levels such as that by Gustavsson and Joelsson (2010). In much of Northern Europe, mineral wool insulation has a major market share, and it has lower environmental impacts than other common insulation materials (Schmidt et al. 2004). There have been studies of the impacts of varying types of insulation completed in the past, such as the LCA carried out by Schmidt et al. (2004) and another by Pargana et al. (2014) who compared the impacts of varying types of insulation based on a functional unit of a specified thermal resistance for a specified area. Additionally, Kaynakli (2012) assessed varying levels of insulation for use in buildings based on life cycle cost, and Mazor et al. (2012) assessed the life-cycle green house gas effects of applying rigid insulation to a building. Furthermore, the study undertaken by Gustavsson and Joelsson (2010) relied on whole buildings as case studies for impact assessment of varying types and levels of insulation applied to varying building typologies. However, none of these indicate an optimal level of insulation for residential buildings and none of these account for the dynamic nature of the energy mix that supplies space heat to buildings throughout their service life, nor do any of these apply and compare multiple impact assessment methods, all of which are done in this study.

In Denmark, while there has been greater recognition of the need for insulation, there has also been a significant shift toward ‘greener’ and less impactful energy production. DEA (2011) reports that such a continuous improvement in the energy production has been planned. In the context of prevailing global warming crises, this type of change in energy production is also possible, if not also likely, on the global scale (Asif and Muneer, 2007). Because of the potential for global human health and environmental impacts of either over or under insulating, an assessment of a broader spectrum of impact categories is necessary.

Sohn et al. (2016) in their recent study, on assessing balance of insulation material and heat required for Danish reference building, have highlighted this shift and its effect on determining optimal levels of insulation. However, Sohn et al. (2016) base their conclusions only on climate change indicator. It is widely recognized that climate change potential is not always indicative of total environmental impact (Laurent et al., 2010; Hauschild et al. 2013). Hence, there is a need for assessing the balance between insulation material and heating of building covering all impacts on the environment, human health, and resource depletion.

Thus, one of the primary areas of focus of this study is adding robustness to previous findings, such as those in Sohn et al. (2016), regarding optimal levels of insulation for residential construction in Denmark by extending the research to incorporate all environmental impacts for the purpose of decision-making. This determined optimum level is intended to both inform policy makers, in order to improve regulations, as well as to inform the producers of mineral wool insulation, in terms of areas of potential improvement in the production process. This is done through the incorporation of MCDA.

Within the LCA community, however, there is significant adherence to the use of certain standard characterization, normalization and weighting methods, such as the ReCiPe single score. Nevertheless, in this study, we provide evidence to indicate that these single scores might not always produce valid results pointing to correct decision support. Hence, in this paper, we assess multiple insulation levels using two Life Cycle Impact Assessment (LCIA) methods coupled with Multiple Criteria Decision Analysis (MCDA). This allows for the generation of two single score assessments, one based on ReCiPe endpoints and the other derived from MCDA of midpoint impacts, which are used to rank the insulation scenarios.

In doing this, we evaluate the use of presently utilized and established assessment methods (climate change potential and single score) and the MCDA method, which we propose as an alternative, for the assessment of optimal insulation levels and also determine the factors that might impact such assessment. This multi-pronged approach allows for a better gauge of the appropriate use of these varying assessment methods for future implementation in LCA of durable materials, and in particular it gives a holistic indication of the effectiveness of the proposed changes in Danish building regulations.

2.0 Methodology

This work uses a novel approach of coupling dynamic assessments based on LCA with MCDA. LCA is used to assess the impact of various insulation levels and energy necessary to fulfill the heating requirements of the living space in the buildings. The results from the LCA are subsequently used to derive single scores. One single score is derived in accordance with established impact assessment methods, while for the second single score method we introduce a new approach for aggregating impact indicators using MCDA. A comparison of these two methods is shown in Figure 1. These are both also compared to a simplified impact assessment using climate change potential as an indicator for all impacts. The following sections describe this method in further detail.

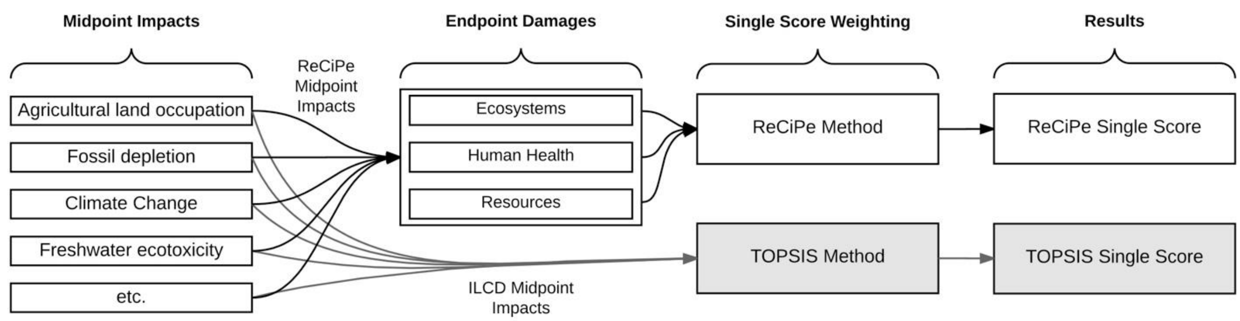

Figure 1: *Comparison of ReCiPe and TOPSIS MCDA analytical methods*

2.1 Life Cycle Assessment

One of the components used in this work is life cycle assessment, which is applied with the goal of determining an optimal level of mineral wool insulation for average SFDH in Denmark. To do this, a functional unit was defined as ‘reference house heated for 50 years’. The ‘reference house’, a single storey detached home with a gross heated floor area of 151.2 m^2, is further described by Sohn et al. (2016). This functional unit represents a trade-off between the materials necessary to insulate, including major incremental building materials, and the energy required for heating the building with the specified amount of insulation over the course of the building’s 50-year service life. The system for this assessment includes the production of insulation and related incremental building materials and their transport, as well as the production and transport of the energy used in the provision of space heating.

In addition, we have modelled a Danish heat mix based on projections for the future Danish energy supply. This modelling effort allows for a better representation of the dynamic nature of the heat mix and associated future impacts of providing heat than could be achieved with the use of a static energy mix based on the current energy market (Sohn et al., 2016). In the LCA model, the energy provision required to fulfill the functional unit was based on a heat loss model suggested for use for Danish SFDH (Aggerholm and Sørensen, 2011; Sohn et al., 2016). Further details on the heat loss modelling and the LCA methodology that were used in this work can be found in Sohn et al. (2016).

In this study, two quite different methods were used for impact assessment to cover the different uncertainties associated with methodological choices. ILCD 2011, which provides only midpoints, is the first impact assessment method (EC, 2010). The second impact assessment method used in this study was ReCiPe method (Goedkoop, 2013). The ReCiPe method provides both midpoint (potentials) and endpoint (damages) impact levels. The ReCiPe endpoints are further normalized and then aggregated into a single score. This was done for three cultural perspectives, hierarchist, individualist, and egalitarian as well as a further three weightings based on the endpoint results derived relying on the hierarchical cultural perspective: equal weighting, emphasis on human health, and emphasis on ecosystem (i.e. environmental impacts), which are detailed in Supplementary information (SI) I Part 1. All the product system modelling and impact assessment hereof was carried out in OpenLCA version 1.4.1 (Green Delta 2015).

2.2 Multi-criteria Analysis

Many methods in MCDA are available that can be used to process midpoint impact indicators and obtain a single score. The most commonly used methods are Simple Weighted Sum Method (WSM), AHP, PROMEETHE, Compromise Programming, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Figueira et al., 2005; Hwang and Yoon, 1981; Yoon and Hwang, 1995). We employed TOPSIS for obtaining single scores based on ILCD midpoints, because of the wide applications of TOPSIS for similar problems and the mathematical approach used in TOPSIS (Behzadian et al., 2012; Kalbar et al., 2015, 2012). TOPSIS works by selecting the best alternative from a group of scenarios, each having been evaluated against a set of criteria. In this study, the insulation and heat provision scenarios are assessed based on ILCD midpoint impacts. Each impact is then weighted, based on different weighting schemes (refer to Table SI I.1 and Table SI I.2 in SI I, Part 1). Based on the input of evaluated scenarios, TOPSIS then generates two artificial scenarios, an ideal alternative (the best possible idealized scenario i.e. in this case, the scenario with lowest possible midpoint impacts) and a negative ideal alternative (the worst possible idealized scenario i.e. in this case, the scenario with highest possible midpoint impacts). All other scenarios are then measured against these two idealized scenarios, and each scenario is assigned a score based on the relative closeness to the ideal alternative and distance from the negative ideal scenario. More details on the methodological details can be found in Hwang and Yoon (1981), Yoon and Hwang (1995) and Kalbar et al. (2012).

2.3 Building insulation levels and heat energy scenarios

In the present study we have focused primarily on a hypothetical reference house constructed in 2015 which is heated throughout its 50-year service life (2015 to 2065) using the Danish heat mix (this scenario will be referred to hereafter as the 2015-mix scenario). As previously mentioned we have considered the dynamic nature of the heat grid mix, integrating a linear interpolation of the projected heat mix available from 2015-2050 (Rasmussen 2012) for 2050-2065. However, to observe the sensitivity in the results we have also created the following hypothetical heat energy supply scenarios.

1. Building constructed in 2015 and heated with energy obtained using only solar energy (2015 – Solar scenario)
2. Building constructed in 2015 and heated with energy obtained using only wind energy (2015 – wind scenario)
3. Building constructed in 2015 and heated with energy obtained using only nuclear energy (2015 – nuclear scenario)
4. Building constructed in 2015 and heated with energy obtained using only hydro energy (2015 – hydro scenario)

Ten insulation scenarios (IS) were tested using these 4 alternative energy scenarios and the 2015 dynamic energy mix. The IS were developed based on a linear increase of insulation thickness (and total mass) in accordance with the three regulatory levels of insulation present in the Danish Building Regulations, BR10 (DEV 2010). These insulation levels range from a level that represents a minimally insulated home (IS1) to a super-insulated home (IS10), these are outlined in Table 1 and are further detailed in previous work by Sohn et al. (2016).

Table 1: *Description of insulation depths for IS1-10 (insulation scenarios) in accordance with Danish regulatory, BR10 (DEV 2010), energy classification.*

	Meets BR 2010*		Meets LE2015*					Meets BK2020*		
	IS1	IS2	IS3	IS4	IS5	IS6	IS7	IS8	IS9	IS10
wall	100	150	200	250	300	350	400	450	500	550
roof	200	275	350	425	500	575	650	725	800	875
floor	200	250	300	350	400	450	500	550	600	650

*Based on only building energy use calculations

3.0 Results and discussion

This study was undertaken because, while climate change potential was used in a previous study by Sohn et al. (2016), there were other midpoint impact indicators that exhibited trends that differed from the trends exhibited by the climate change impact potential (Sohn et al. 2016). This observation, that Sohn et al. (2016) made, is further evident from the midpoint impacts potentials obtained from the ILCD method as well as the midpoint and endpoint impacts potentials obtained from the ReCiPe method for all the five cases (i.e. 2015 Danish heat mix, 2015-solar, 2015-wind, 2015-nuclear, and 2015-hydro), which are provided in in SI II, Tables SI II.1-5. The results in these tables show that there is disagreement among the indicators regarding the optimal insulation scenario/insulation level. For example, as shown in Table SI II.1H, the results of the 2015-mix scenario in terms of climate change impact indicator identifies IS5 as the best insulation level. However, when using Freshwater Eutrophication as the critical indicator, IS7 is identified as the best insulation level. The next sub-sections discuss the results of the differing heat provision scenarios in detail.

3.1 2015-mix scenario

Single scores were obtained by further processing results from the ILCD method (midpoints) and directly from the ReCIPe methods (endpoints) for all ten scenarios for each of the weighing schemes. The ILCD midpoint impacts were processed using the TOPSIS method, which provided a score for each scenario, which we refer to as ILCD-TOPSIS single score. The endpoint impacts from the ReCiPe method were normalized and aggregated in order to obtain a single score. These scores were used to decide the ranks of each insulation scenario. The single scores (provided in SI I) and respective rank (shown in Figure 2) were obtained using ILCD-TOPSIS method and ReCiPe method for each scenario.

The results in terms of ranks for the 2015-mix scenario are presented in Figure 2, where the ranks of each IS for each respective weighting scheme are plotted as bars. Figure 2 indicates that IS5 is the best insulation level if the 2015-mix scenario, which corresponds to the Danish district heating mix, is used. However, as we can see from Figure 2, there is some disagreement between the ranks obtained by ILCD-TOPSIS single score and the ReCiPe single score. For example, when the egalitarian perspective is applied, IS3 insulation level is ranked at seven in accordance with the ReCiPe single score while the ILCD-TOPSIS method gives a rank of 5.

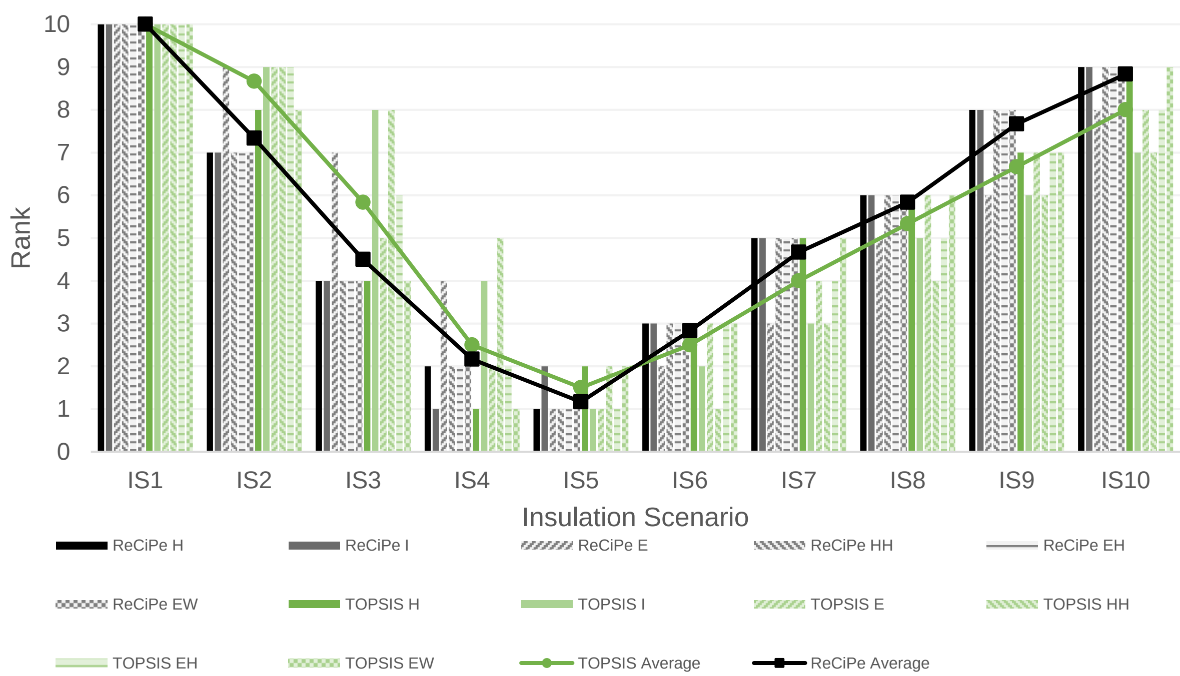

Figure 2: *Ranking in order from 1 (most preferable) to 10 (least preferable) for insulation scenarios 1-10 using district heating (2015-Mix energy scenario) based on ReCiPe and TOPSIS single score values for Hierarchist, Individualist, Egalitarian, Equal Weights, Higher weight to Human Health, and Higher Weight to Ecosystem perspectives and an average ranking based on all perspectives for both ReCiPe and TOPSIS analysis methods. Average lines showing overall agreement between the two analysis methods.*

To further verify and analyze this disagreement between rankings, we plotted the internally normalized and weighted ILCD midpoints of the best alternatives identified by the ILCD-TOPSIS method and the ReCiPe method against the Positive Ideal Solution (PIS) in radar plots (see Figure 3 and SI I, Part 2). In our case, PIS is the theoretically best scenario (i.e. theoretical scenario having lowest impacts). Figure 3 shows these radar plots for the 2015-mix scenario. The scenario that most closely matches the shape of the PIS (shown in yellow fill with a black outline) is the best scenario from the ten IS under evaluation. As seen from these graphs, the disagreement varies according to cultural perspective and weighing scheme. Most importantly, the ReCiPe and ILCD-TOPSIS single scores tend to show agreement with climate change indicator in a considerable number of cases.

To investigate the nature of this agreement, i.e. whether it is due to the mathematical principles of the methods applied for aggregation of indicators or if it is because of a relation of climate change indicator with other impact categories, we considered four additional hypothetical scenarios. These additional scenarios are described in the methodology section. As these additional scenarios all are dependent on renewable energy, and hence less dependent on fossil energy, there is less correlation with climate change indicator than in the 2015-mix scenario. The results of this analysis are presented in next sub-section, 3.2. These results support the findings of the recent study by Kalbar et al. (2016a), where, with the help of large empirical data set, it was shown that ReCiPe single score does not provide correct decision support.

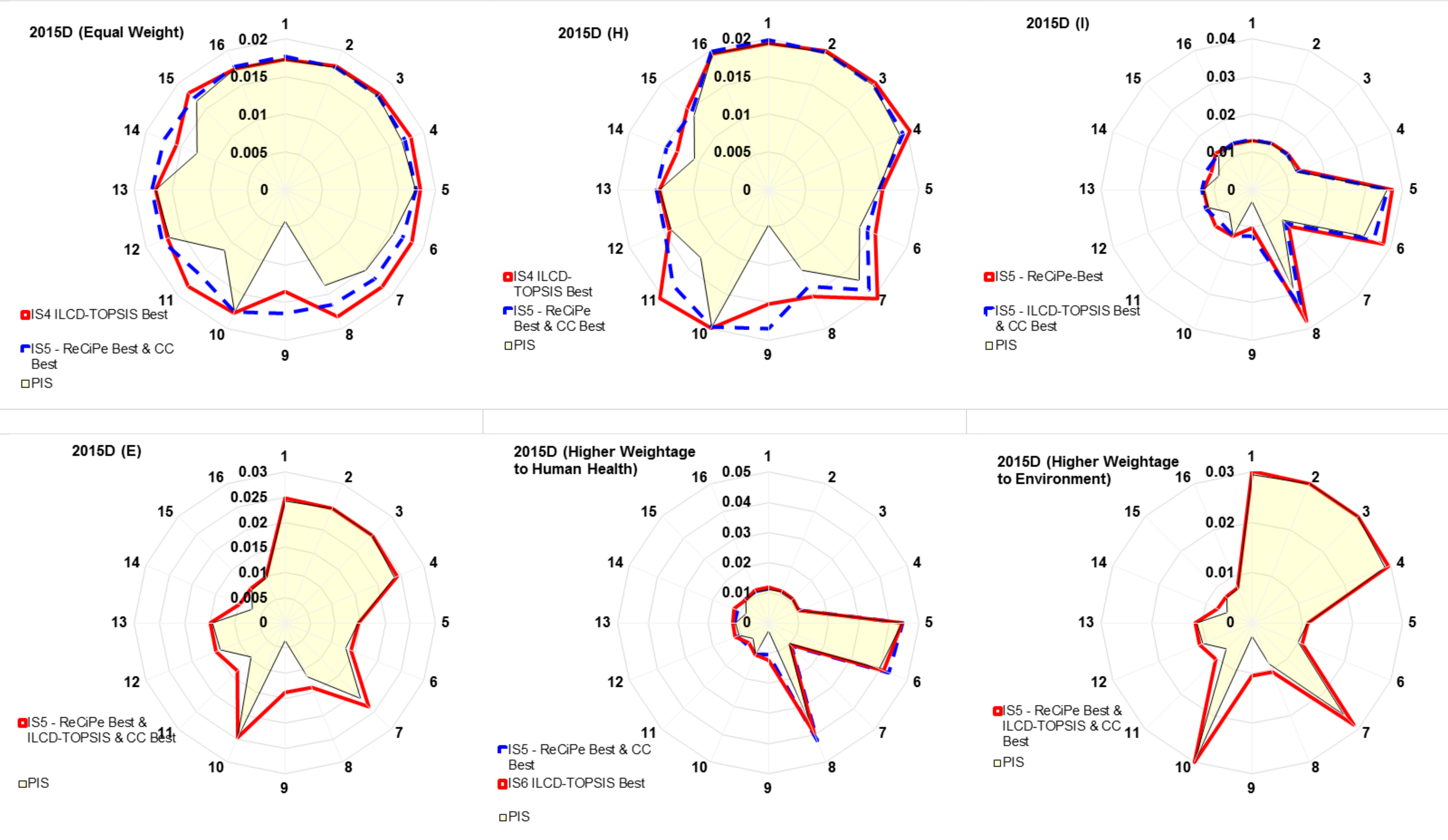

Figure 3: *Radar graphs showing the difference in the best identified scenario by the two single scores and climate change indicator for the three cultural perspectives (hierarchist, individualist, and egalitarian) and the three further weightings (equal weighting, emphasis on human health, and emphasis on ecosystem). PIS is positive ideal solution.*

1: Acidification 2: Climate change 3: Freshwater ecotoxicity 4: Freshwater eutrophication 5: Human toxicity – carcinogenics 6: Human toxicity - non-carcinogenics 7: Ionizing radiation – ecosystems 8: Ionizing radiaton - human health 9: Land use 10: Marine eutrophication 11: Ozone depletion 12: Particulate matter/Respiratory inorganics 13: Photochemical ozone formation 14: Resource depletion – mineral 15: Resource depletion - fossils ,renewables and water 16: Terrestrial eutrophication

3.2 Renewable energy scenarios

The radar graphs for the four renewable energy scenarios as applied with the 10 insulation scenarios are provided in SI II (See Figure SI I.1A-X). These graphs show that for these scenarios, more disagreement appears between the ILCD-TOPSIS method and ReCiPe methods in the renewable energy scenarios. Figure 4 and Figure 5, which show plots similar to Figure 2, illustrate greater disagreement between the ILCD-TOPSIS method and the ReCiPe method for 2015-nuclear and wind scenario respectively.

To further investigate the causes for such disagreement, contribution analyses for the IS5 2015-mix scenario and the IS5 2015-nuclear scenario were undertaken, as the nuclear scenario showed greater disagreement with the 2015-mix scenario than did the wind scenario. The results of the contribution analyses are provided in the SI I (Part 3, contribution analysis results), detailing two heating scenarios: the 2015 dynamic energy mix and the nuclear energy supply. Figures SI I.2 and SI I.3, show that mineral wool production process is the largest contributor across a majority of the impacts for both of the energy scenarios. However, based on an average across all ReCiPe midpoint impact categories, the contribution of mineral wool production in the 2015-mix scenario is 38% whereas in the 2015-nulcear scenario it is 59%. This finding suggests that impacts in the 2015-mix scenario are more dependent on climate change indicator, with the mineral wool production being entirely driven by fossil fuel consumption (Deutche Rockwool 2012) and the Danish heat mix as represented in the 2015 dynamic energy mix also being more fossil fuel driven than that of the alternative fuel scenarios. In contrast, in the 2015-nuclear scenario other processes (primarily the nuclear energy production), which are not carbon driven, contributes 41% to all impacts. These observations suggest that the renewable energy scenarios overall impacts are less dependent on climate change indicator. This finding illuminates the disagreement between the TOPSIS method and single score results related with the influence of the climate change indicator on single score results both in ILCD and ReCiPe method in renewable energy scenarios. Thus, we see that lesser dependency on carbon fuels tended to create more variation in the midpoints (see midpoints results in Table SI II.1H-5H in SI II). Such midpoints when aggregated into single score tend to disagree with the climate change indicator based ranks. For example, Figure SI I.1 G-L, in SI I, showing radar plots for 2015-nuclear scenario, in each of these plots there is disagreement among climate change indicator, ReCiPe single score, and/or ILCD-TOPSIS methods. Similarly, disagreement among the methods is also found in the wind and solar energy scenarios. However, when we compare the radar plots for the 2015-mix scenario in Figure 3, all six radar plots of different weighing schemes climate change indicator based optimal IS level tend to match either the ReCiPe single score or with ILCD-TOPSIS based single score. This fits with the findings of Kalbar et al. (2016a) that have shown with a hypothetical set of indicator data that ranks obtained by applying TOPSIS well represent weighting scheme chosen by LCA practitioner.

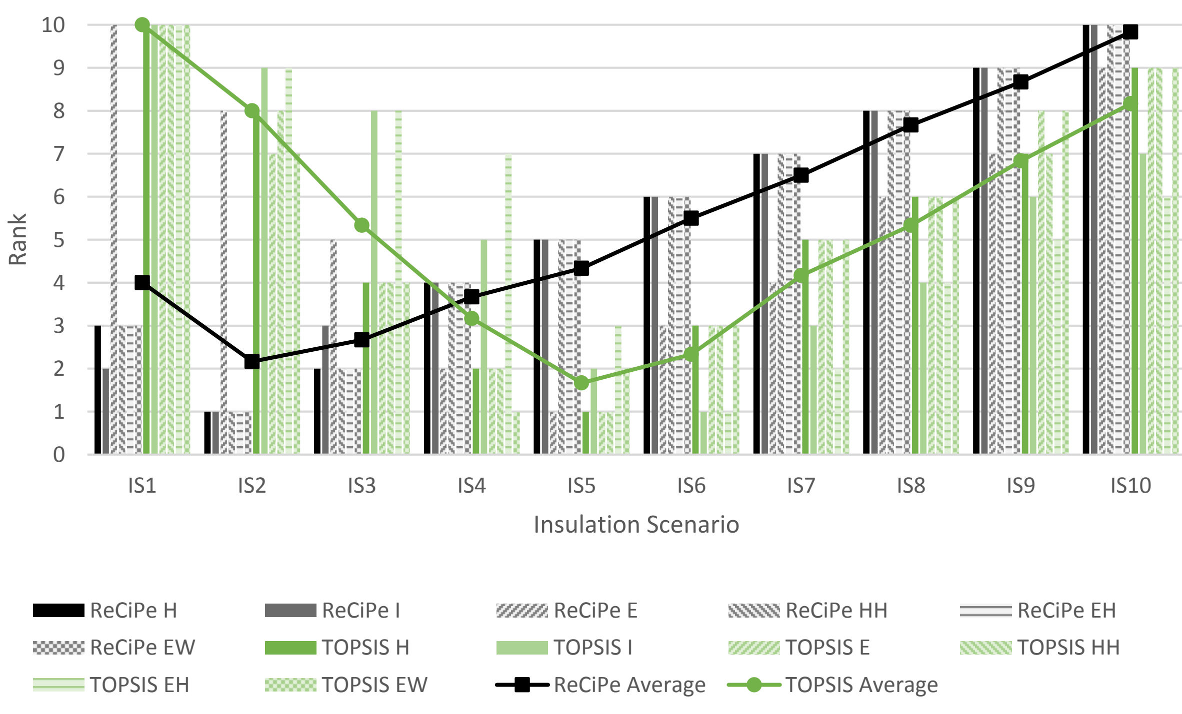

Figure 4: *Ranking in order from 1 (most preferable) to 10 (least preferable) for insulation scenarios 1-10 using nuclear energy heating based on ReCiPe and TOPSIS single score values for Hierarchist, Individualist, Egalitarian, Equal Weights, Higher weight to Human Health, and Higher Weight to Ecosystem perspectives and an average*

ranking based on all perspectives for both ReCiPe and TOPSIS analysis methods. Average lines showing overall disagreement between the two analysis methods.

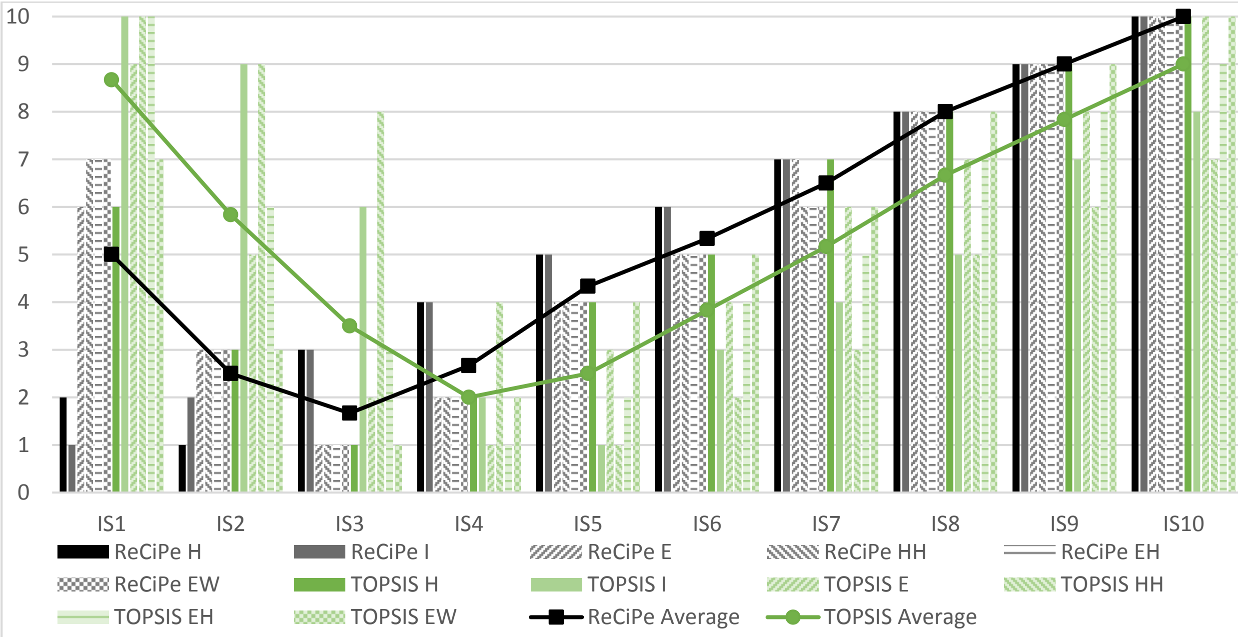

Figure 5: *Ranking in order from 1 (most preferable) to 10 (least preferable) for insulation scenarios 1-10 using wind energy heating based on ReCiPe and TOPSIS single score values for Hierarchist, Individualist, Egalitarian, Equal Weights, Higher weight to Human Health, and Higher Weight to Ecosystem perspectives and an average ranking based on all perspectives for both ReCiPe and TOPSIS analysis methods. Average lines showing overall disagreement between the two analysis methods.*

Figures SI I.1G-L in SI I also present how the alternative identified by TOPSIS very closely matches the shape of PIS (marked by yellow fill with black outline) compared to those identified by the ReCiPe single score and climate change indicator. This shows that the application of the ILCD-TOPSIS approach can be used as a cross-validation of the results from other established methods such as the ReCiPe single score.

3.3 Areas of Improvement for sustainable heating and insulation service for buildings

The contribution analysis reveals a primary area of improvement regarding the usage of fossil fuels in both the energy production and for mineral wool production processes. Such improvements are planned in Denmark for the heat energy mix, and as discussed in section 3.4.1 such improvements are not included in the results of this study. Furthermore, while production of mineral wool is one of the important potential area of improvement, in the context of a house constructed in the present (viz. 2015), future developments in mineral wool production are not relevant, as current production methods establish the impact of materials at the time of construction. This creates an offset in the impact profile, as the delay in impact for ongoing processes such as heat provision allow for technological improvements “along the road” to potentially reduce overall impacts. For the 2015 mix scenario, it isn’t until 2036 that a house built according to IS1 would have a greater impact than a house built according to IS5, and it is not until 2048 that IS1 exhibits a greater impact than IS8 (Figure 6). This gives a number of years for technological improvements in heat production before the greater total impacts of lower levels of insulation (such as IS3) are realized, potentially prolonging the payback time of greater levels of insulation. Additionally, should the service life of the building exceed 50 years, it seems likely, given the use of the 2015 dynamic energy mix with no further improvements after 2050 that IS8 could eventually become preferable to IS5, though such a preference would not be realized until more than several decades after the end of the assumed 50-year service life (see Figure 6).

Given current research regarding the service life of buildings, an average service life of between 67 and 83 years could be assumed instead of the used 50-year service life (Thorsted & Østergaard, 2016). And, if we (very conservatively) assume no further improvement in the energy system after 50 years, for IS8 to be preferable, it would require an approximately 94-year service life. In such a case, an 83-year service life is not enough time for IS8 to become preferable. Furthermore, the assumption that no changes would be made to energy production in the years after 2065 is likely incorrect. Rather, it is likely that improvements would continue to be made to the energy mix, pushing the insulation production impacts payback point further in to the future. Thus, in the case of the service life necessary to make IS8 the optimal choice, and given current insulation production methods, the likelihood of improvements in energy production after 50-years from the present result in the conclusion that equal total impacts between IS8 and IS5 might never become practically attainable.

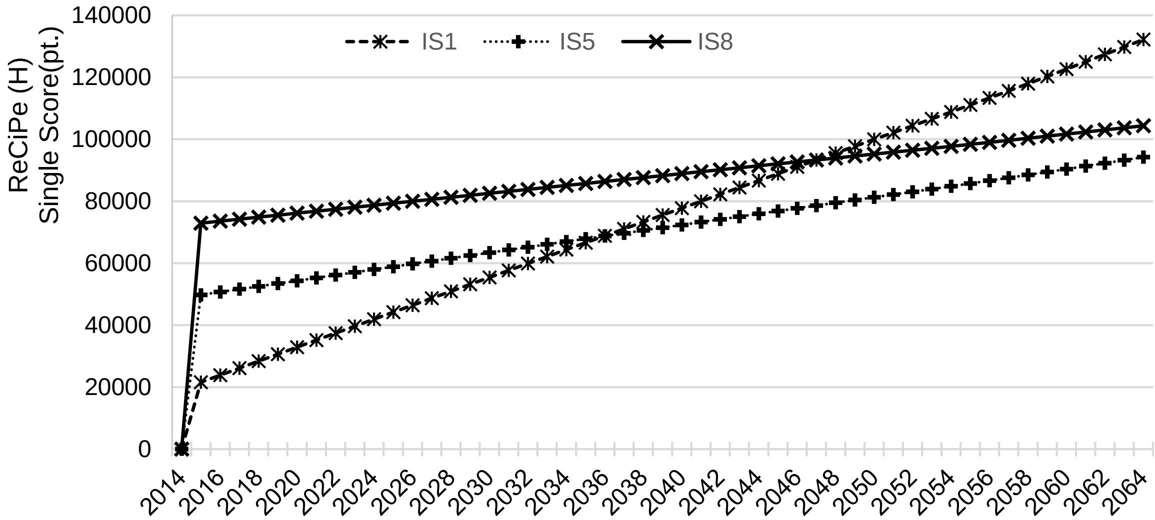

Figure 6: Building impact (ReCiPe (H) single score) throughout the service life of the building for IS1, 5, and 8 recorded at the projected time of impact occurrence, assuming the use of a dynamic district heating mix following political projections

As previously described, the magnitude of the difference between the impacts of heating versus insulation can range from much greater (in the case of IS1) to much less (in the case of IS8). Unforeseen technological innovation or simple change in energy mix composition has the potential to greatly reduce the overall impact throughout the course of a buildings service life, as can be seen by comparing the absolute values for impacts from the varying energy mix scenarios (see SI II Tables SI II.1-5). Conversely, the impacts of the insulation production are embedded at the time of construction and thus are not subject to change. Moreover, because the impacts of insulation production happen immediately at the time of construction, a decrease in the impact of production of insulation could with much greater level of certainty reduce the overall impact of an optimally insulated home. For example, if the impact of the production of insulation were reduced by 60%, making IS8 an optimal insulation level, the total impact of heating and insulating an optimally insulated reference house throughout its service life is reduced by over 35%, given the use of the 2015 dynamic energy mix (see Figure 7 and Table SI II.3). With such a reduction in the impact of producing insulation, even the then non-optimally insulated IS5 would have over 31% lower impact for heating and insulation in relation to the optimally insulated house with present insulation production methods (IS5). In both of these cases there is a fixed reduction of the impact of providing insulation, whereas if that reduction was to be obtained through increased levels of insulation assuming a much greater service life (beyond 125 years), the level of uncertainty in obtaining the given reduction would be very high and the risk of much greater impact from unforeseen shortening of the service life of a particular installation of insulation in a building (i.e. from a fire) would be commensurably greater.

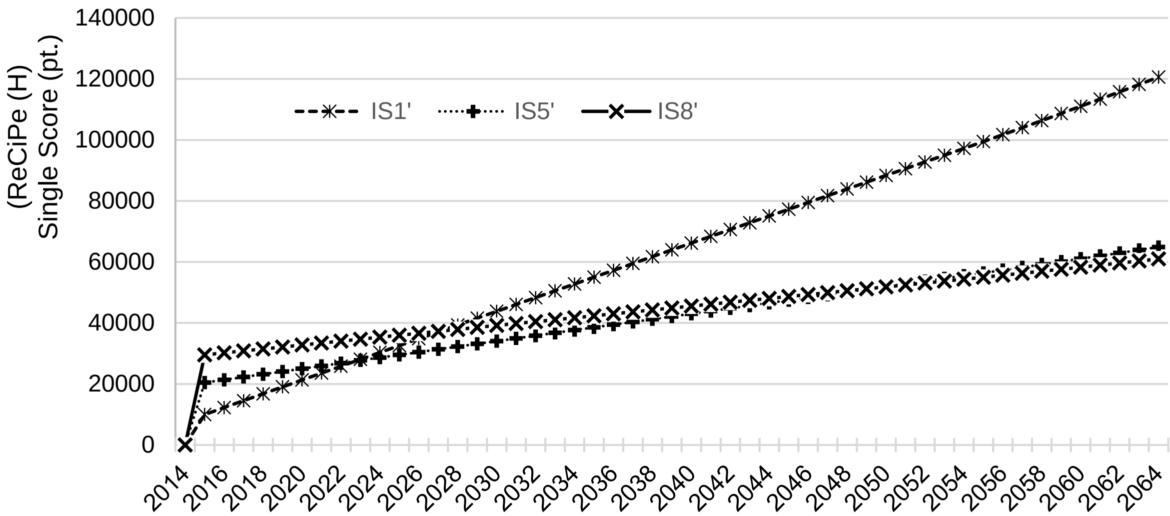

Figure 7: *Building impact (ReCiPe (H) single score) throughout the service life of the building for IS1, 5, and 8 recorded at the projected time of impact occurrence, assuming the use of a dynamic district heating mix following political projections with the impact of production of insulation reduced by 60%*

3.4 Limitations of the study:

As the present study is an extension of the work reported in Sohn et al. (2016) all the limitations discussed in that study are also applicable here. The following are some of the specific limitations that need to be take into account while using the results from present study:

The dynamic energy mix used for calculation of the impacts of the district heating grid energy provision is, in practical application for the LCA conducted in this study, only partially dynamic. While the energy mix used for the 2015 dynamic energy mix heat supply scenario is 'dynamic' in so much as the mix of energy sources used to represent the Danish energy mix for assessment changes annually according to the energy mix projection, the processes used for provision of energy in the mix do not change in such a dynamic way. That is to say, the processes that use energy in the provision of heat, e.g. electric boilers and heat pumps, are modeled using a static energy supply that often includes a large fraction of coal and other fossil fuels. These processes were used because development of dynamic processes for all elements of the energy mix was deemed well beyond the scope of this study. However, implicit in the political plans for the development of the Danish heat-energy mix is also plans to reduce or eliminate fossil fuels from the energy mix in its entirety (DEA 2011). The result of the use of these static processes in the dynamic energy mix results in a minor overestimation of the impact of providing heat, which becomes more apparent with time. However, this overestimation is much less than it would be if purely static energy mix were used, but it does represent a limitation of the study.

Also, the use of single score impact assessment was deemed necessary to account for the differing trends across impact categories, and TOPSIS was applied as a check on the ReCiPe single score results to help prevent over-prioritization of climate change impacts. However, individual impacts which may be of importance in specific geographical regions might still be missed if only relying on the single score assessment. Because of this, midpoint impacts should always be referenced in final decision-making. While not presented in the main body of the paper, the full results of the LCA including midpoint and endpoint impacts are included in SI II. Furthermore, while it was deemed outside of the scope of the present work, the authors suggest that a full study of alternative fuels for the mineral wool production process could play a significant role in aiding companies and regulators in optimizing future insulation production and regulation.

5.0 Conclusions

The findings of this study were obtained in an attempt to answer questions regarding choice of impact assessment method via a case study attempting to answer three problems, viz., determining ideal insulation levels, gauging the effectiveness of environmental impact reduction measures in current Danish building regulations, and areas of potential improvement in mineral wool insulation production.

With regard to impact assessment method, our study shows that choice of impact assessment methods will yield different results, particularly when the impacts of the system are not dominated by fossil fuel driven processes. When the impact indicators are strongly related with the climate change indicator for all processes, it does not matter which method (i.e. ReCiPe single score or TOPSIS) is employed for determining best insulation level. This follows closely with previous findings regarding generalized assessments (Huijbregts et al., 2010). However, in more complex systems (i.e. when the processes include both impacts that are independent from climate change potential such as in renewable energy production and those that are dependent on climate change potential such as fossil fuel energy production), the findings of this study indicate that it is necessary to apply more sophisticated processing method for obtaining single score. This confirms the findings of Laurent et al. (2010) and Kalbar et al. (2016b), that climate change indicator is not always indicative of overall impacts for complex systems. Thus, our study demonstrates the advantage of the TOPSIS method for obtaining single scores in cases where midpoint impacts do not all correlate well with climate change. The TOPSIS method proved to provide rankings commensurate with the applied weighting scheme.

Furthermore, in all assessments, the optimal insulation level indicated is below the insulation levels necessary to meet 2020 requirements when using only insulation to reduce energy consumption. And, the contribution analysis indicates that there are areas of improvement present in the process for production of mineral wool insulation. Primarily, a shift from the use of fossil fuels for process heat in the cupola furnace could have significant impact. However, given the likelihood that there will be more-reduced reliance on fossil fuels than indicated by the district heating production processes used in this analysis, it is likely that the impacts of heat production will also be reduced. The overall impact of these reductions indicate that only somewhat higher levels of insulation than presently required by Danish law could be beneficial in the future even if the impacts of the production of insulation were reduced. And, the magnitude of impact reduction necessary in the production of insulation to make superinsulation (IS8 or above) an optimal insulation level is unlikely. But, reduction in the impact of insulation production directly results in an overall reduction of the impact of heating and insulating residential homes, making it a good candidate for attempts to reduce the overall environmental impact of residential buildings in Denmark.

Because of this, from a whole-system perspective, the development of the process used for production of mineral wool insulation should be considered an important element for the overall reduction in impacts induced by new residential construction. This also indicates that building regulations could potentially be improved by including elements that account for the impacts of the insulation products used to fulfill the energy requirements. Such an inclusion could greatly reduce the overall environmental impacts from heating of house. And, due to its ability to account for the varied characteristics of the mid-point impacts found in complex systems, the inclusion of TOPSIS as a method of obtaining single score results in the assessments would be beneficial to the development of such regulations.

Acknowledgements:

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Supplementary Information I

Life Cycle based Dynamic Assessment Coupled with Multiple Criteria Decision Analysis: A Case Study of Determining an Optimal Building Insulation Level

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Part 1: Weighting

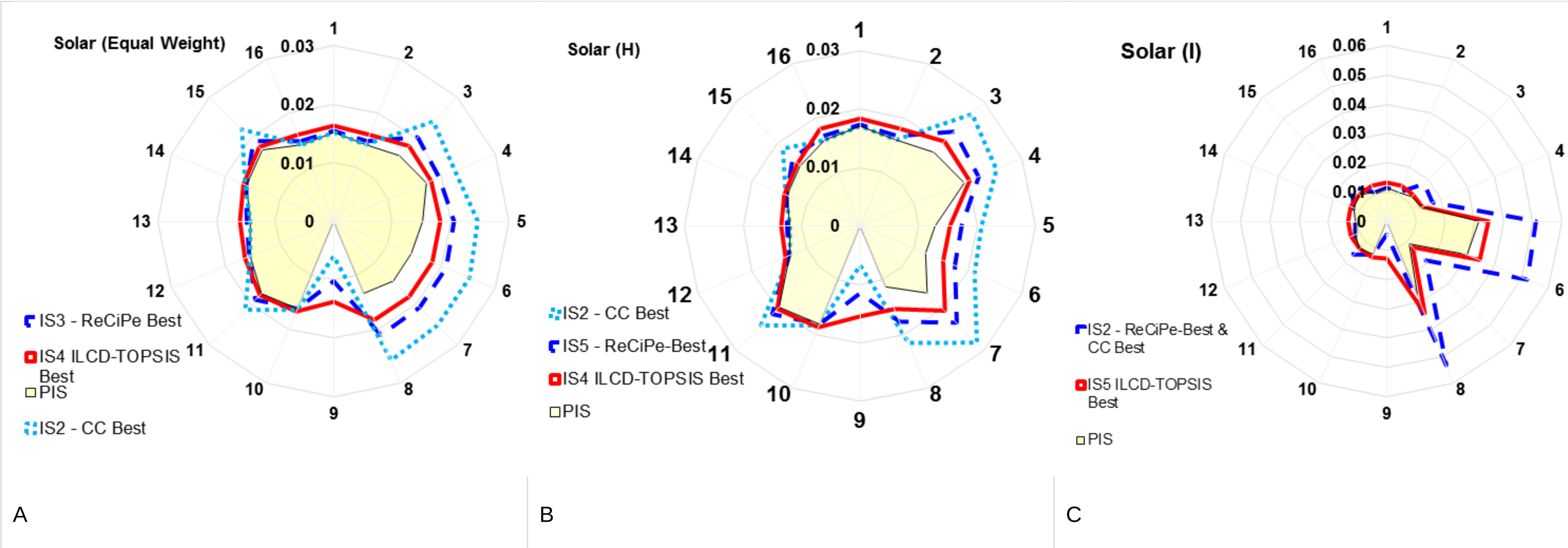
Table SI I.1: *ReCiPe Endpoint weights applied to calculate single score*

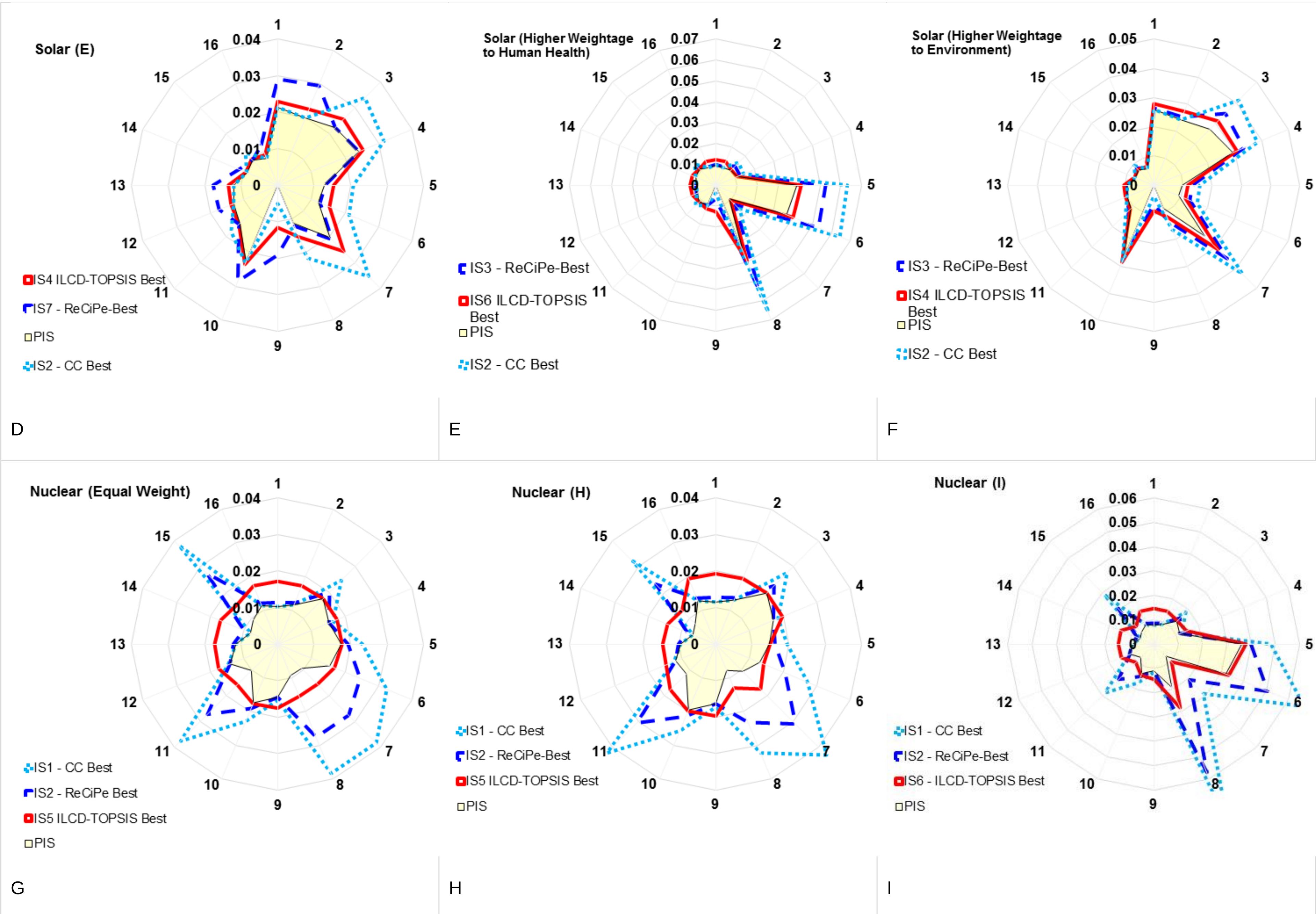
Perspective/ Scenario	Human health	Ecosystems	Resources	Total
Hierarchist	300	400	300	1000
Individualist	550	250	200	1000
Egalitarian	300	500	200	1000
Equal Weights	333.33	333.33	333.33	1000
Higher weight to Human Health	700	150	150	1000
Higher Weight to Ecosystem	150	700	150	1000

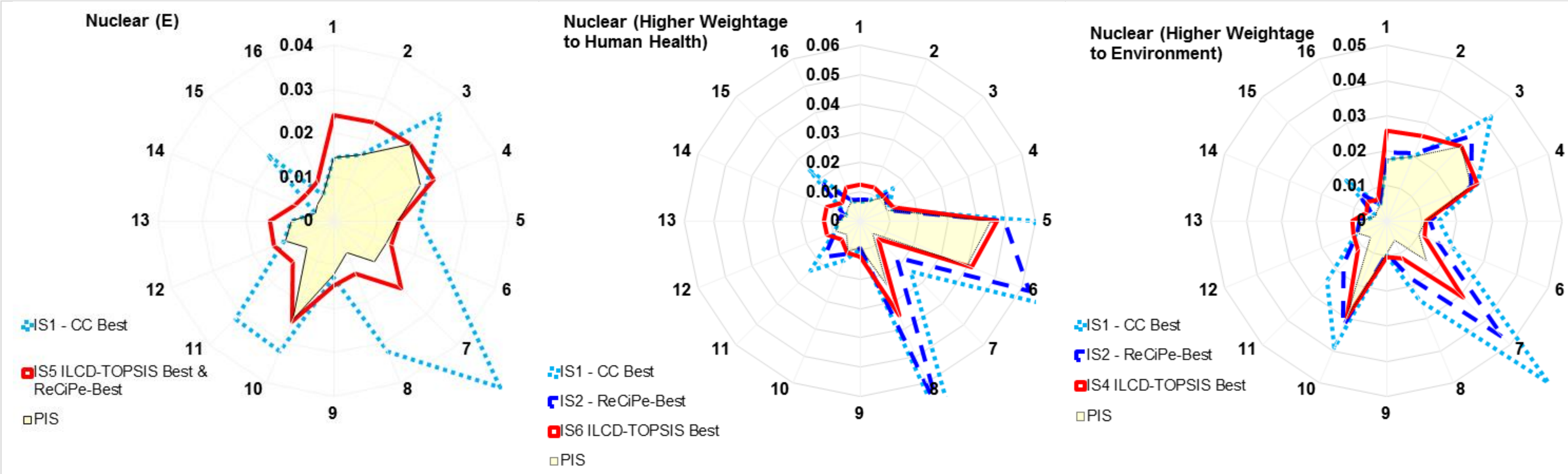
Table SI I.2: *ILCD-TOPSIS single score weights applied to calculate single score*

	Perspective/Scenario				
Impact Category	**Hierarchist**	**Individualist**	**Egalitarian**	**Higher Weight to Human Health**	**Higher Weight to Ecosystem**
Acidification	400	200	500	200	800
Climate change	400	200	500	200	800
Freshwater ecotoxicity	400	200	500	200	800
Freshwater eutrophication	400	200	500	200	800
Human toxicity - carcinogenics	300	550	300	800	300
Human toxicity - non-carcinogenics	300	550	300	800	300
Ionizing radiation - ecosystems	400	200	500	200	800
Ionizing radiaton - human health	300	550	300	800	300
Land use	400	200	300	200	300
Marine eutrophication	400	200	500	200	800
Ozone depletion	400	200	300	200	300
Particulate matter/Respiratory inorganics	300	200	300	200	300
Photochemical ozone formation	300	200	300	200	300
Resource depletion - mineral, fossils and renewables	300	200	200	200	200
Resource depletion - water	300	200	200	200	200
Terrestrial eutrophication	400	200	200	200	200

Part 2: Renewable energy scenarios



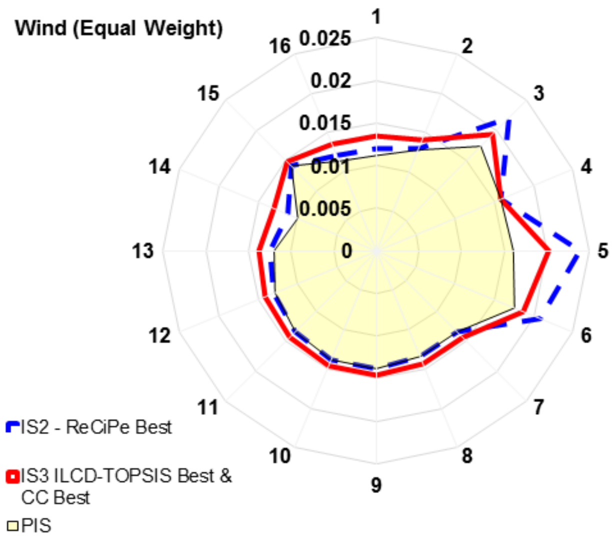

Solar (E)
IS4 ILCD-TOPSIS Best
IS7 - ReCiPe-Best
PIS
IS2 - CC Best
D
Solar (Higher Weightage to Human Health)
IS3 - ReCiPe-Best
IS6 ILCD-TOPSIS Best
PIS
IS2 - CC Best
E
Solar (Higher Weightage to Environment)
IS3 - ReCiPe-Best
IS4 ILCD-TOPSIS Best
PIS
IS2 - CC Best
F
Nuclear (Equal Weight)
IS1 - CC Best
IS2 - ReCiPe Best
IS5 ILCD-TOPSIS Best
PIS
G
Nuclear (H)
IS1 - CC Best
IS2 - ReCiPe-Best
IS5 ILCD-TOPSIS Best
PIS
H
Nuclear (I)
IS1 - CC Best
IS2 - ReCiPe-Best
IS6 - ILCD-TOPSIS Best
PIS
I


Nuclear (E)
IS1 - CC Best
IS5 ILCD-TOPSIS Best & ReCiPe-Best
PIS
Nuclear (Higher Weightage to Human Health)
IS1 - CC Best
IS2 - ReCiPe-Best
IS6 ILCD-TOPSIS Best
PIS
Nuclear (Higher Weightage to Environment)
IS1 - CC Best
IS2 - ReCiPe-Best
IS4 ILCD-TOPSIS Best
PIS

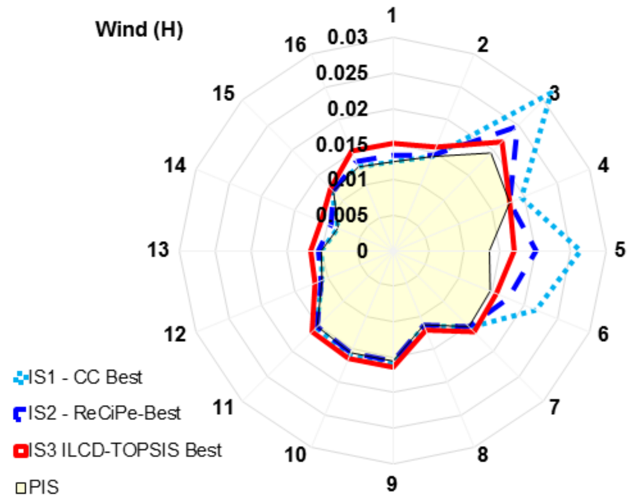
J

K

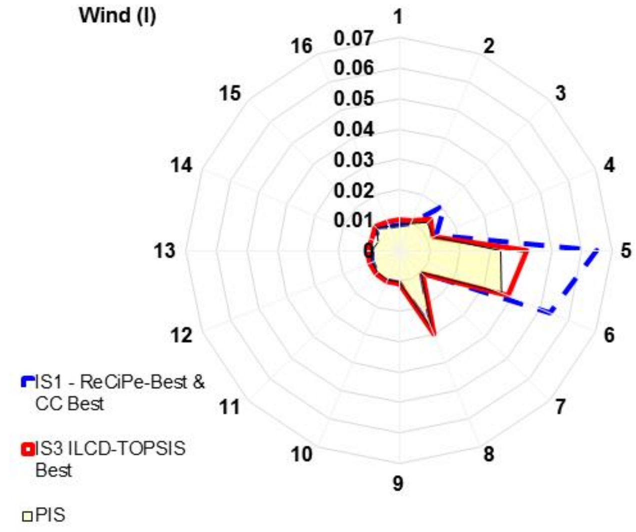
L


Wind (Equal Weight)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0.025
0.02
0.015
0.01
0.005
0
IS2 - ReCiPe Best
IS3 ILCD-TOPSIS Best & CC Best
PIS

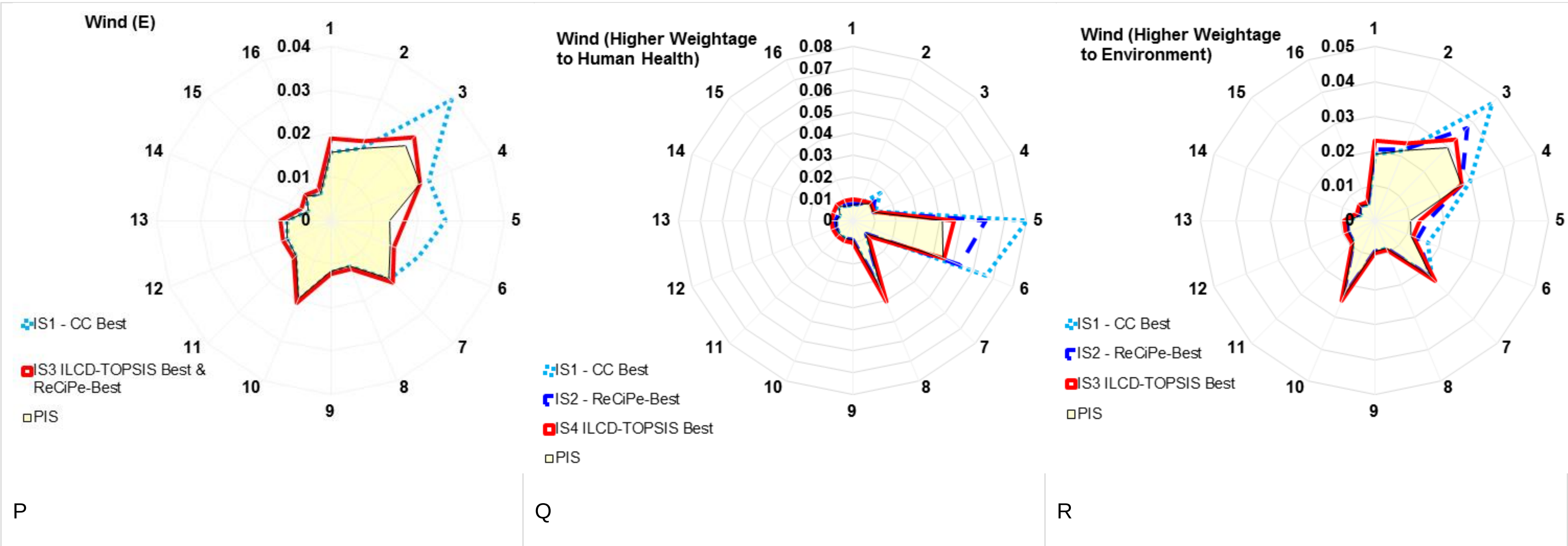
M


Wind (H)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0.03
0.025
0.02
0.015
0.01
0.005
0
IS1 - CC Best
IS2 - ReCiPe-Best
IS3 ILCD-TOPSIS Best
PIS

N


Wind (I)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
IS1 - ReCiPe-Best & CC Best
IS3 ILCD-TOPSIS Best
PIS

O



Wind (E)
IS1 - CC Best
IS3 ILCD-TOPSIS Best & ReCiPe-Best
PIS
P
Wind (Higher Weightage to Human Health)
IS1 - CC Best
IS2 - ReCiPe-Best
IS4 ILCD-TOPSIS Best
PIS
Q
Wind (Higher Weightage to Environment)
IS1 - CC Best
IS2 - ReCiPe-Best
IS3 ILCD-TOPSIS Best
PIS
R

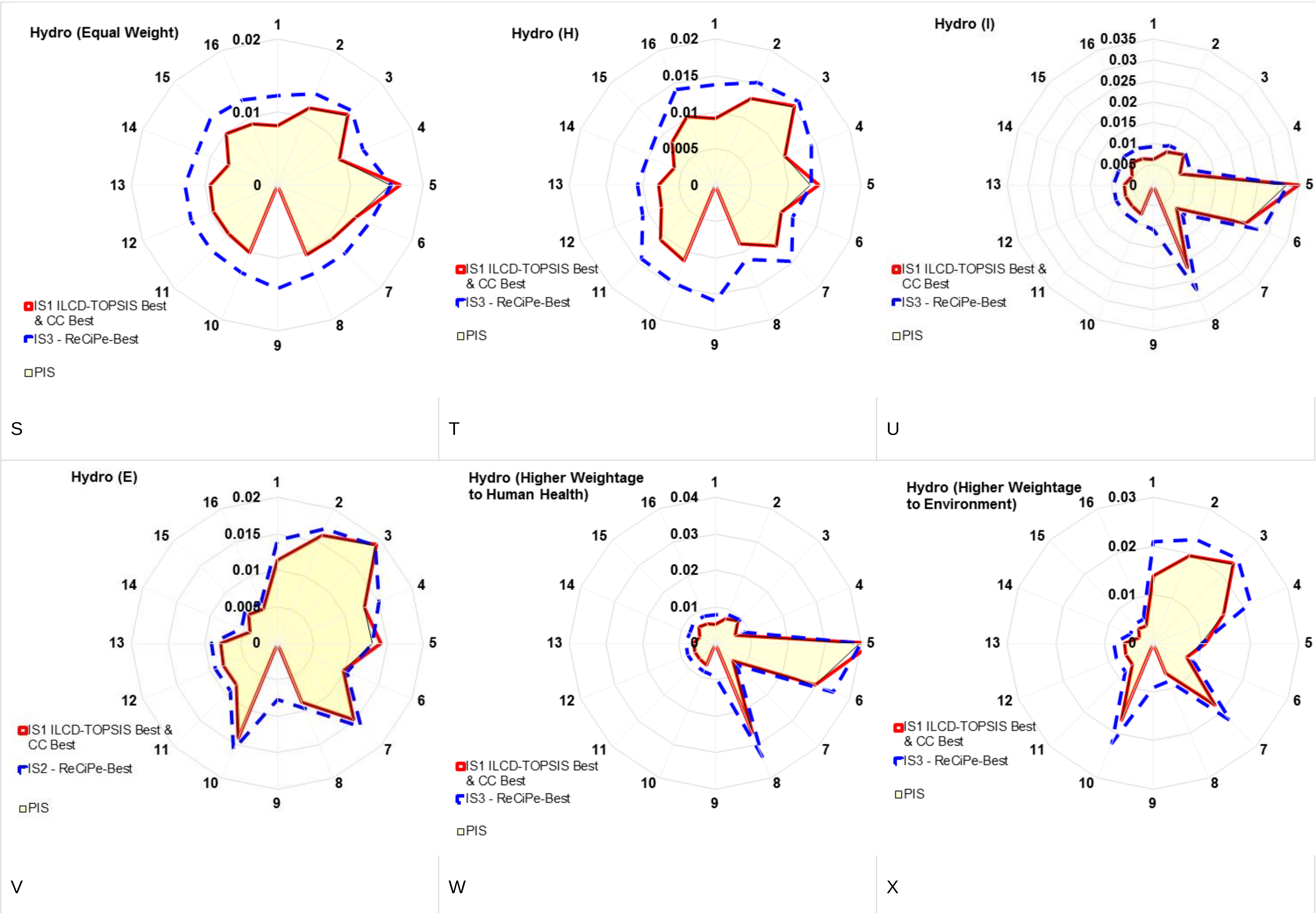

Hydro (Equal Weight)
IS1 ILCD-TOPSIS Best & CC Best
IS3 - ReCiPe-Best
PIS
S
Hydro (H)
IS1 ILCD-TOPSIS Best & CC Best
IS3 - ReCiPe-Best
PIS
T
Hydro (I)
IS1 ILCD-TOPSIS Best & CC Best
IS3 - ReCiPe-Best
PIS
U
Hydro (E)
IS1 ILCD-TOPSIS Best & CC Best
IS2 - ReCiPe-Best
PIS
V
Hydro (Higher Weightage to Human Health)
IS1 ILCD-TOPSIS Best & CC Best
IS3 - ReCiPe-Best
PIS
W
Hydro (Higher Weightage to Environment)
IS1 ILCD-TOPSIS Best & CC Best
IS3 - ReCiPe-Best
PIS
X

Figure SI I.1A-X: *Radar graphs showing the difference in the best identified insulation scenario by ReCiPe and TOPSIS single scores and climate change indicator for the four renewable energy scenarios: solar, nuclear, wind, and hydro. PIS is positive ideal solution.*

1: Acidification 2: Climate change 3: Freshwater ecotoxicity 4: Freshwater eutrophication 5: Human toxicity – carcinogenics 6: Human toxicity - non-carcinogenics 7: Ionizing radiation – ecosystems 8: Ionizing radiaton - human health 9: Land use 10: Marine eutrophication 11: Ozone depletion 12: Particulate matter/Respiratory inorganics 13: Photochemical ozone formation 14: Resource depletion – mineral 15: Resource depletion - fossils ,renewables and water 16: Terrestrial eutrophication

Part 3: Contribution analysis results

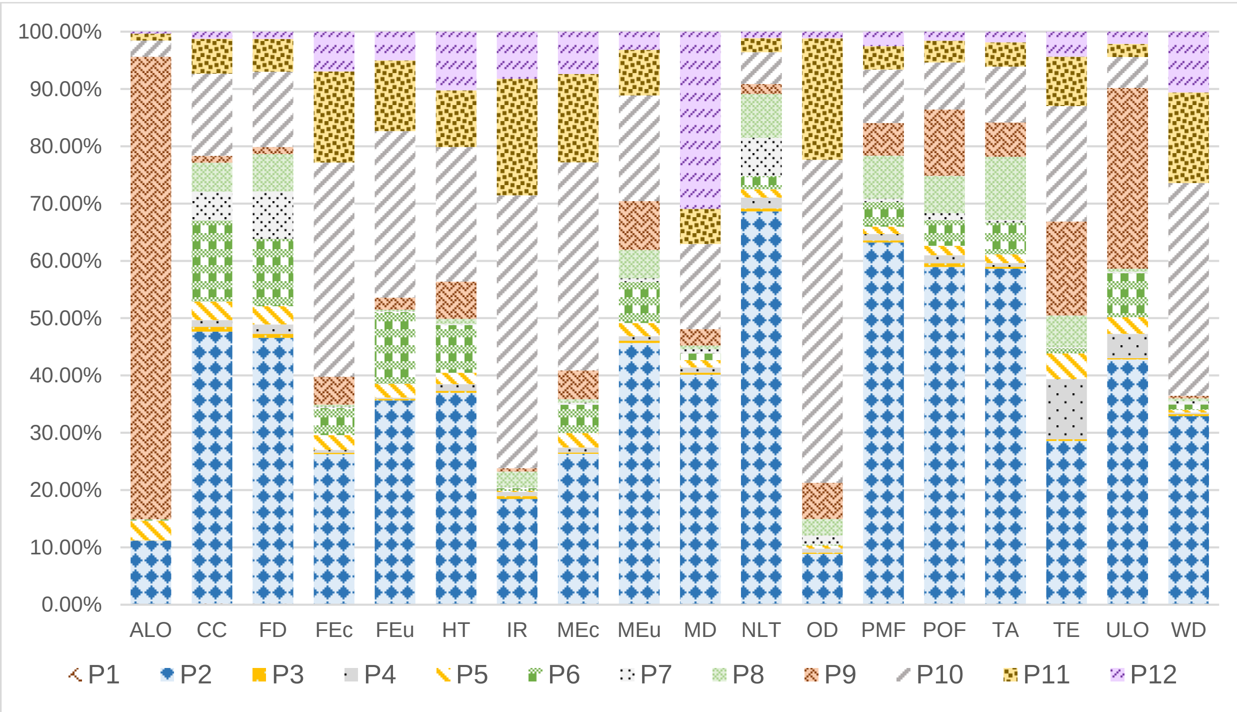


Figure SI I.2: *Process contributions for ReCiPe midpoint (Hierarchist) impacts for insulation scenario 5 with 2015 dynamic energy mix heat scenario.*

P1=clay brick production | clay brick | APOS, S, P2=rock wool production, packed | rock wool, packed | APOS, S, P3=roof tile production | roof tile | APOS, S, P4=transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S, P5=electricity, high voltage, production mix | electricity, high voltage | APOS, S, P6=heat and power co-generation, hard coal | heat, district or industrial, other than natural gas | APOS, S, P7=heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | heat, district or industrial, natural gas | APOS, S, P8=heat and power co-generation, oil | heat, district or industrial, other than natural gas | APOS, S, P9=heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | heat, district or industrial, other than natural gas | APOS, S, P10=heat production, air-water heat pump 10kW | heat, air-water heat pump 10kW | APOS, S, P11=heat production, borehole heat exchanger, brine-water heat pump 10kW | heat, borehole heat pump | APOS, S, P12=operation, solar collector system, evacuated tube collector, one-family house, for combined system | heat, central or small-scale, other than natural gas | APOS, S

ALO=Agricultural land occupation, CC=Climate Change, FD=Fossil depletion, FEc=Freshwater ecotoxicity, FEu=Freshwater eutrophication, HT=Human toxicity, IR=Ionizing radiation, MEc=Marine ecotoxicity, MEu=Marine eutrophication, MD=Metal depletion, NLT=Natural land transformation, OD=Ozone depletion, PMF=Particulate matter formation, POF=Photochemical oxidant formation, TA=Terrestrial acidification, TE=Terrestrial ecotoxicity, ULO=Urban land occupation, WD=Water depletion

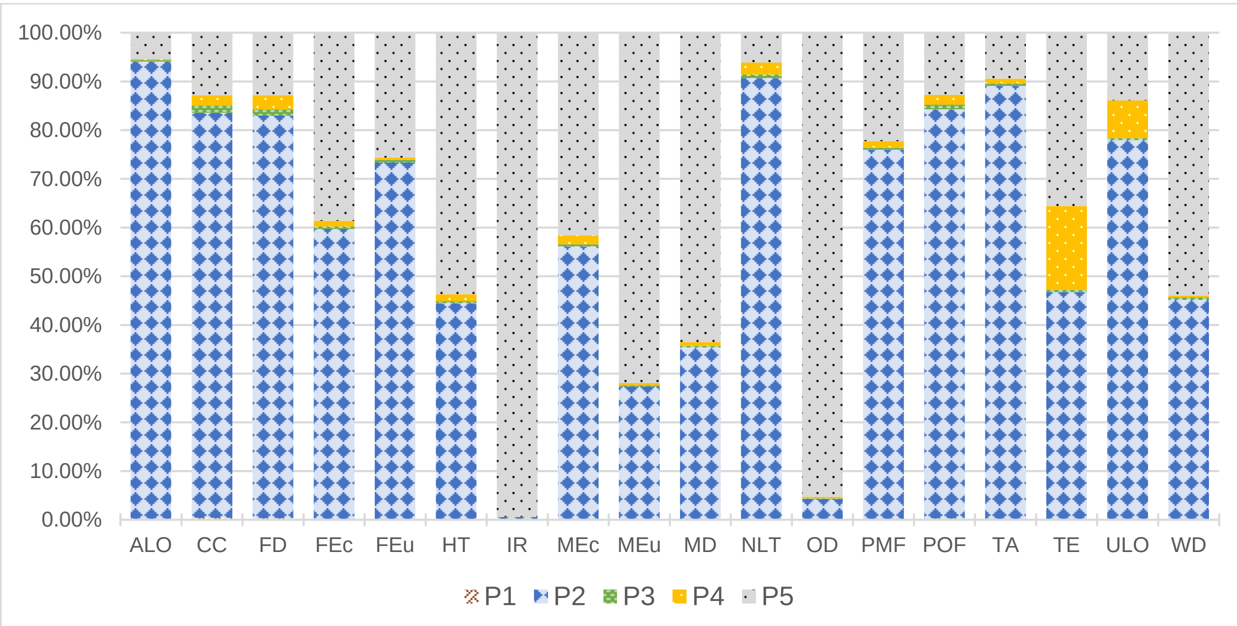


Figure SI I.3: *Process contributions for ReCiPe midpoint (Hierarchist) impacts for insulation scenario 5 with nuclear energy heat scenario*

P1=clay brick production | clay brick | APOS, S, P2=rock wool production, packed | rock wool, packed | APOS, S, P3=roof tile production | roof tile | APOS, S, P4=transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S, P5=electricity production, nuclear, boiling water reactor | electricity, high voltage | APOS, S.

ALO=Agricultural land occupation, CC=Climate Change, FD=Fossil depletion, FEc=Freshwater ecotoxicity, FEu=Freshwater eutrophication, HT=Human toxicity, IR=Ionizing radiation, MEc=Marine ecotoxicity, MEu=Marine eutrophication, MD=Metal depletion, NLT=Natural land transformation, OD=Ozone depletion, PMF=Particulate matter formation, POF=Photochemical oxidant formation, TA=Terrestrial acidification, TE=Terrestrial ecotoxicity, ULO=Urban land occupation, WD=Water depletion

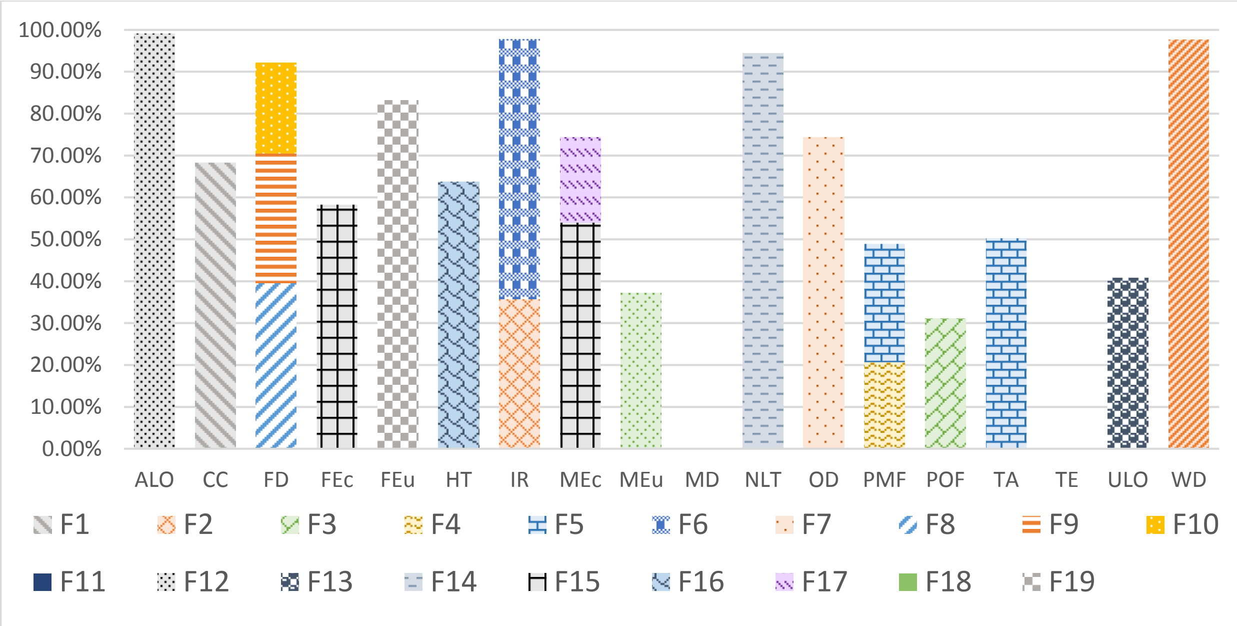


Figure SI I.4: *Flow contributions for ReCiPe midpoint (Hierarchist) impacts for insulation scenario 5 with 2015 dynamic energy mix heat scenario. Flows with less than 20% contribution are omitted, hence some of the bars do not sum up to 100%.*

F1=Carbon dioxide, fossil, F2=Carbon-14, F3=Nitrogen oxides, F4=Particulates, < 2.5 um, F5=Sulfur dioxide, F6=Radon-222, F7=Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113, F8=Coal, hard, unspecified, in ground, F9=Gas, natural, in ground, F10=Oil, crude, in ground, F11=Water, turbine use, unspecified natural origin, F12=Occupation, forest, intensive, normal, F13=Occupation, traffic area, road embankment, F14=Transformation, from forest, intensive, normal, F15=Copper, ion, F16=Manganese, F17=Nickel, ion, F18=Nitrate, F19=Phosphate.

ALO=Agricultural land occupation, CC=Climate Change, FD=Fossil depletion, FEc=Freshwater ecotoxicity, FEu=Freshwater eutrophication, HT=Human toxicity, IR=Ionizing radiation, MEc=Marine ecotoxicity, MEu=Marine eutrophication, MD=Metal depletion, NLT=Natural land transformation, OD=Ozone depletion, PMF=Particulate matter formation, POF=Photochemical oxidant formation, TA=Terrestrial acidification, TE=Terrestrial ecotoxicity, ULO=Urban land occupation, WD=Water depletion

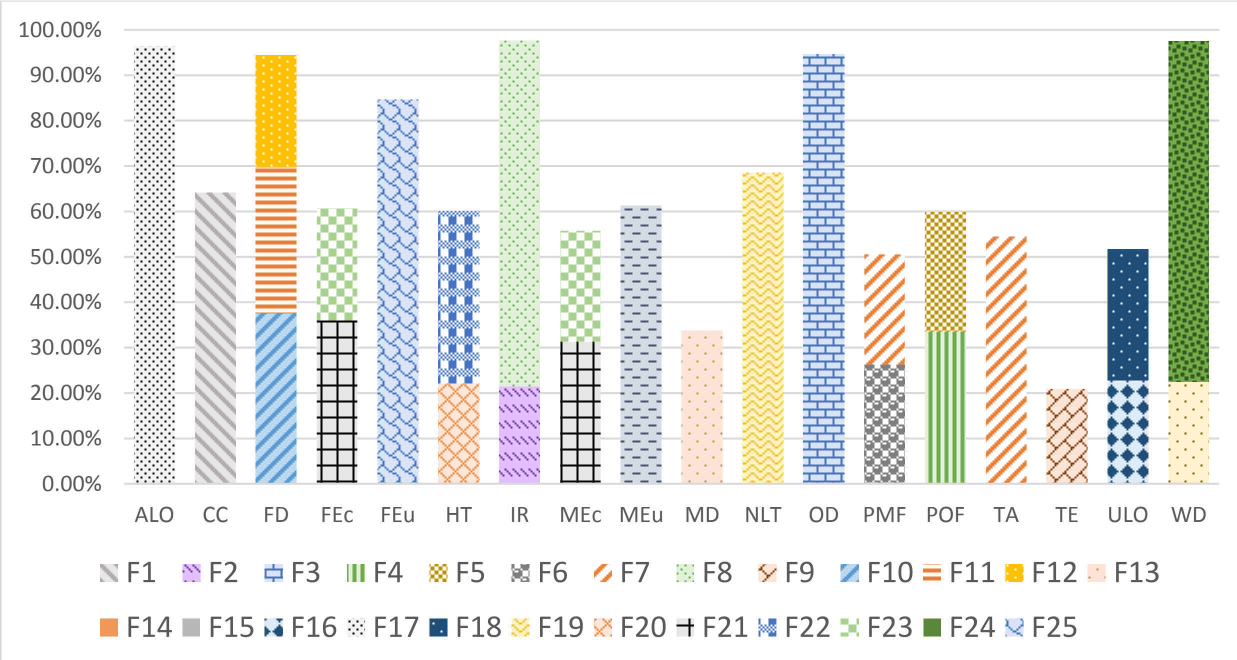


Figure SI I.5: *Flow contributions for ReCiPe midpoint (Hierarchist) impacts for insulation scenario 5 with nuclear energy heat scenario. Flows with less than 20% contribution are omitted.*

F1=Carbon dioxide, fossil, F2=Carbon-14, F3=Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114, F4=Nitrogen oxides, F5=NMVOC, non-methane volatile organic compounds, unspecified origin, F6=Particulates, < 2.5 um, F7=Sulfur dioxide, F8=Radon-222, F9=Copper, F10=Coal, hard, unspecified, in ground, F11=Gas, natural, in ground, F12=Oil, crude, in ground, F13=Uranium, in ground, F14=Water, cooling, unspecified natural origin, F15=Water, turbine use, unspecified natural origin, F16=Occupation, dump site, F17=Occupation, forest, intensive, normal, F18=Occupation, mineral extraction site, F19=Transformation, from forest, intensive, normal, F20=Arsenic, ion, F21=Copper, ion, F22=Manganese, F23=Nickel, ion, F24=Nitrate, F25=Phosphate.

ALO=Agricultural land occupation, CC=Climate Change, FD=Fossil depletion, FEc=Freshwater ecotoxicity, FEu=Freshwater eutrophication, HT=Human toxicity, IR=Ionizing radiation, MEc=Marine ecotoxicity, MEu=Marine eutrophication, MD=Metal depletion, NLT=Natural land transformation, OD=Ozone depletion, PMF=Particulate matter formation, POF=Photochemical oxidant formation, TA=Terrestrial acidification, TE=Terrestrial ecotoxicity, ULO=Urban land occupation, WD=Water depletion

Table SI I.3: *ReCiPe single score impact values for insulation scenarios 1, 5, and 8 after the 1st and 50th year of service assuming the use of 2015 energy mix for heat provision*

	Standard insulation			Reduced impact insulation		
	IS1	IS5	IS8	IS1'	IS5'	IS8'
2015	21581	49794	72925	9993	20464	29557
2064	132199	94224	104373	120611	64894	61005

Supplementary Information II

Life Cycle based Dynamic Assessment Coupled with Multiple Criteria Decision Analysis: A Case Study of Determining an Optimal Building Insulation Level

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Acronyms

IS: Insualtion Scenario
H: Hierarchist
I: Individualist
E: Egalitarian
EW: Equal Weights
EH: Higher Weight to Ecosystem
HH: Higher weight to Human Health

2015 Dynamic Energy Mix Detailed LCA results

Table SI II.1A-I: detailed LCA results of IS 1-10 with 2015 Dynamic energy mix scenario for ReCiPe endpoint, ILCD-TOPSIS single score, ILCD Midpoint, and ReCiPe midpoint

A.
ReCiPe (H)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0408	435.0	5.556	132187
IS2	0.0330	354.6	4.467	107727
IS3	0.0297	322.2	4.004	97879
IS4	0.0283	310.5	3.809	94311
IS5	0.0281	310.3	3.763	94219
IS6	0.0286	317.8	3.818	96487
IS7	0.0293	328.1	3.908	99622
IS8	0.0306	343.8	4.068	104370
IS9	0.0320	361.1	4.247	109611
IS10	0.0335	380.0	4.448	115347

B.
ReCiPe (I)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0312	376.9	2.036	207722
IS2	0.0257	308.7	1.632	170139
IS3	0.0237	281.9	1.457	155355
IS4	0.0231	272.9	1.382	150372
IS5	0.0233	273.7	1.361	150824
IS6	0.0240	281.2	1.377	154964
IS7	0.0250	291.2	1.406	160466
IS8	0.0263	305.8	1.461	168496
IS9	0.0278	321.8	1.523	177303
IS10	0.0294	339.2	1.593	186891

C.
ReCiPe (E)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0746	3161.5	5.556	949594
IS2	0.0598	2501.2	4.467	751297
IS3	0.0533	2204.7	4.004	662241
IS4	0.0505	2063.8	3.809	619921
IS5	0.0497	2008.7	3.763	603381
IS6	0.0503	2011.5	3.818	604248
IS7	0.0513	2035.2	3.908	611354
IS8	0.0533	2098.1	4.068	630285
IS9	0.0555	2172.6	4.247	652655
IS10	0.0580	2258.5	4.448	678476

D.
ReCiPe (EW)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0408	435.0	5.556	146869
IS2	0.0330	354.6	4.467	119691
IS3	0.0297	322.2	4.004	108751
IS4	0.0283	310.5	3.809	104785
IS5	0.0281	310.3	3.763	104684
IS6	0.0286	317.8	3.818	107204
IS7	0.0293	328.1	3.908	110686
IS8	0.0306	343.8	4.068	115962
IS9	0.0320	361.1	4.247	121785
IS10	0.0335	380.0	4.448	128158

E.
ReCiPe (HH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0408	435.0	5.556	305349
IS2	0.0330	354.6	4.467	248880
IS3	0.0297	322.2	4.004	226160
IS4	0.0283	310.5	3.809	217941
IS5	0.0281	310.3	3.763	217753
IS6	0.0286	317.8	3.818	223014
IS7	0.0293	328.1	3.908	230278
IS8	0.0306	343.8	4.068	241269
IS9	0.0320	361.1	4.247	253398
IS10	0.0335	380.0	4.448	266670

F.
ReCiPe (EH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0408	435.0	5.556	66114
IS2	0.0330	354.6	4.467	53880
IS3	0.0297	322.2	4.004	48955
IS4	0.0283	310.5	3.809	47169
IS5	0.0281	310.3	3.763	47124
IS6	0.0286	317.8	3.818	48258
IS7	0.0293	328.1	3.908	49825
IS8	0.0306	343.8	4.068	52200
IS9	0.0320	361.1	4.247	54821
IS10	0.0335	380.0	4.448	57690

G.
ILCD-TOPSIS single score

	Hierarchist		Individualist	Egalitarian	Equal Weights	Human Health	Environmental Health
IS1	0.402		0.264	0.331	0.392	0.207	0.266
IS2	0.590		0.516	0.565	0.588	0.493	0.552
IS3	0.720		0.702	0.729	0.724	0.696	0.742
IS4	0.767		0.800	0.798	0.776	0.808	0.827
IS5	0.758		0.833	0.803	0.771	0.856	0.843
IS6	0.725		0.826	0.778	0.738	0.861	0.824
IS7	0.687		0.805	0.744	0.699	0.849	0.794
IS8	0.643		0.774	0.702	0.655	0.825	0.751
IS9	0.602		0.743	0.659	0.612	0.798	0.705
IS10	0.563		0.711	0.617	0.573	0.770	0.658

H.
ILCD Midpoint

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IS1	239	36349	41950	17.31	0.0020	0.0100	0.0163	6419	1481	33.5	0.0180	20.5	99.8	0.003	13.7	405
IS2	202	29240	33457	13.40	0.0016	0.0076	0.0123	4773	2675	27.0	0.0132	17.9	84.8	0.003	10.6	338
IS3	189	26228	29741	11.55	0.0014	0.0064	0.0102	3925	3757	24.3	0.0106	17.3	80.1	0.003	9.1	315
IS4	188	24971	28071	10.56	0.0013	0.0057	0.0091	3415	4803	23.2	0.0090	17.6	80.0	0.004	8.3	310
IS5	192	24684	27530	10.06	0.0012	0.0052	0.0083	3091	5835	23.0	0.0079	18.4	82.3	0.004	7.8	315
IS6	201	25055	27753	9.88	0.0012	0.0050	0.0079	2891	6865	23.4	0.0072	19.6	86.3	0.005	7.7	327
IS7	211	25665	28252	9.81	0.0012	0.0048	0.0076	2733	7903	24.0	0.0065	20.9	91.0	0.005	7.6	343
IS8	224	26723	29270	9.96	0.0013	0.0048	0.0076	2659	8944	25.1	0.0062	22.4	96.9	0.006	7.7	362
IS9	238	27914	30442	10.17	0.0013	0.0048	0.0075	2606	9998	26.2	0.0059	24.0	103.2	0.006	7.8	384
IS10	252	29240	31767	10.45	0.0014	0.0049	0.0076	2576	11063	27.5	0.0056	25.7	109.8	0.007	8.0	407

1=Acidification, Mole H+ eq., 2=Climate change, kg CO2 eq., 3=Freshwater ecotoxicity, CTUe, 4=Freshwater eutrophication, kg P eq., 5=Human toxicity - carcinogenics, CTUh, 6=Human toxicity - non-carcinogenics, CTUh, 7=Ionizing radiation - ecosystems, CTUe, 8=Ionizing radiaton - human health, kg U235 eq., 9=Land use, kg SOC, 10=Marine eutrophication, kg N eq., 11=Ozone depletion, kg CFC-11 eq., 12=Particulate matter/Respiratory inorganics, kg PM2.5 eq., 13=Photochemical ozone formation, kg C2H4 eq., 14=Resource depletion - mineral, fossils and renewables, kg Sb eq., 15=Resource depletion - water, m3, 16=Terrestrial eutrophication, Mole N eq.

I.
ReCiPe Midpoint (H)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IS1	35670	36816	9548	832	17.8	16386	6434	767	8.45	1885	6.20	0.0181	59.7	102.5	183	3.74	563	129423
IS2	26109	29745	7692	629	13.8	12754	4784	580	6.75	1480	5.60	0.0132	51.7	87.1	155	2.92	451	99357
IS3	21057	26797	6909	527	11.8	11047	3934	487	6.02	1294	5.57	0.0106	49.8	82.3	145	2.54	403	84765
IS4	17916	25619	6586	468	10.8	10162	3424	433	5.69	1202	5.80	0.0090	50.4	82.1	144	2.34	381	76768
IS5	15820	25418	6518	432	10.3	9729	3099	400	5.59	1161	6.18	0.0079	52.5	84.5	147	2.25	375	72395
IS6	14422	25881	6622	413	10.1	9601	2898	383	5.65	1155	6.65	0.0072	55.6	88.7	154	2.23	380	70457
IS7	13259	26585	6789	399	10.0	9581	2740	371	5.76	1162	7.16	0.0066	59.1	93.5	162	2.23	387	69372
IS8	12562	27741	7073	396	10.1	9768	2666	368	5.97	1192	7.75	0.0062	63.2	99.5	172	2.28	402	69931
IS9	11986	29034	7392	396	10.3	10012	2613	368	6.22	1229	8.35	0.0059	67.6	105.9	183	2.34	419	70945
IS10	11530	30463	7747	398	10.6	10316	2583	371	6.50	1272	8.99	0.0057	72.3	112.8	194	2.42	438	72416

1=Agricultural land occupation, m2*a, 2=Climate Change, kg CO2 eq, 3=Fossil depletion, kg oil eq, 4=Freshwater ecotoxicity, kg 1,4-DB eq, 5=Freshwater eutrophication, kg P eq, 6=Human toxicity, kg 1,4-DB eq, 7=Ionising radiation, kg U235 eq, 8=Marine ecotoxicity, kg 1,4-DB eq, 9=Marine eutrophication, kg N eq, 10=Metal depletion, kg Fe eq, 11=Natural land transformation, m2, 12=Ozone depletion, kg CFC-11 eq, 13=Particulate matter formation, kg PM10 eq, 14=Photochemical oxidant formation, kg NMVOC, 15=Terrestrial acidification, kg SO2 eq, 16=Terrestrial ecotoxicity, kg 1,4-DB eq, 17=Urban land occupation, m2*a, 18=Water depletion, m3

2015 Solar Scenario Detailed LCA results

Table SI II.2A-I: detailed LCA results of IS 1-10 with Solar energy scenario for ReCiPe endpoint, ILCD-TOPSIS single score, ILCD Midpoint, and ReCiPe midpoint

A.
ReCiPe (H)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0146	286.2	4.161	87115
IS2	0.0141	247.6	3.464	75320
IS3	0.0148	237.9	3.213	72326
IS4	0.0160	240.7	3.154	73153
IS5	0.0175	250.5	3.203	76116
IS6	0.0193	265.1	3.324	80544
IS7	0.0211	281.6	3.473	85541
IS8	0.0231	301.5	3.671	91556
IS9	0.0251	322.5	3.885	97915
IS10	0.0273	344.6	4.116	104619

B.
ReCiPe (I)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0134	178.7	2.879	98867
IS2	0.0130	166.2	2.238	91872
IS3	0.0136	169.5	1.935	93640
IS4	0.0147	179.8	1.777	99274
IS5	0.0161	194.1	1.699	107102
IS6	0.0178	211.1	1.675	116461
IS7	0.0194	229.3	1.670	126461
IS8	0.0213	249.5	1.701	137549
IS9	0.0232	270.4	1.742	149054
IS10	0.0251	292.0	1.793	160981

C.
ReCiPe (E)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0482	4411.2	4.161	1324211
IS2	0.0407	3399.8	3.464	1020650
IS3	0.0383	2913.2	3.213	874628
IS4	0.0381	2650.4	3.154	795774
IS5	0.0391	2510.6	3.203	753848
IS6	0.0409	2453.6	3.324	736757
IS7	0.0430	2425.6	3.473	728382
IS8	0.0458	2453.4	3.671	736787
IS9	0.0486	2496.9	3.885	749870
IS10	0.0517	2556.0	4.116	767640

D.
ReCiPe (EW)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0146	286.2	4.161	96792
IS2	0.0141	247.6	3.464	83686
IS3	0.0148	237.9	3.213	80360
IS4	0.0160	240.7	3.154	81278
IS5	0.0175	250.5	3.203	84570
IS6	0.0193	265.1	3.324	89491
IS7	0.0211	281.6	3.473	95042
IS8	0.0231	301.5	3.671	101726
IS9	0.0251	322.5	3.885	108790
IS10	0.0273	344.6	4.116	116239

E.
ReCiPe (HH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0146	286.2	4.161	200969
IS2	0.0141	247.6	3.464	173830
IS3	0.0148	237.9	3.213	166982
IS4	0.0160	240.7	3.154	168943
IS5	0.0175	250.5	3.203	175829
IS6	0.0193	265.1	3.324	186093
IS7	0.0211	281.6	3.473	197669
IS8	0.0231	301.5	3.671	211594
IS9	0.0251	322.5	3.885	226311
IS10	0.0273	344.6	4.116	241825

F.
ReCiPe (EH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0146	286.2	4.161	43565
IS2	0.0141	247.6	3.464	37667
IS3	0.0148	237.9	3.213	36170
IS4	0.0160	240.7	3.154	36584
IS5	0.0175	250.5	3.203	38067
IS6	0.0193	265.1	3.324	40282
IS7	0.0211	281.6	3.473	42781
IS8	0.0231	301.5	3.671	45790
IS9	0.0251	322.5	3.885	48970
IS10	0.0273	344.6	4.116	52323

G.
ILCD-TOPSIS single score

	Hierarchist	Individualist	Egalitarian	Equal Weights	Human Health	Environmental Health
IS1	0.570	0.354	0.496	0.538	0.279	0.453
IS2	0.685	0.539	0.647	0.666	0.499	0.634
IS3	0.716	0.684	0.727	0.717	0.675	0.744
IS4	0.686	0.751	0.732	0.701	0.769	0.773
IS5	0.637	0.761	0.699	0.660	0.801	0.751
IS6	0.585	0.744	0.655	0.612	0.798	0.707
IS7	0.536	0.721	0.610	0.566	0.782	0.660
IS8	0.489	0.692	0.564	0.520	0.760	0.610
IS9	0.448	0.664	0.522	0.480	0.737	0.564
IS10	0.414	0.637	0.486	0.446	0.714	0.523

H.
ILCD Midpoint

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IS1	143	12912	80085	15.45	0.0038	0.0131	0.0192	7134	-3574	17.2	0.0026	15.9	54.5	0	10.9	193
IS2	133	12389	60876	12.07	0.0029	0.0098	0.0144	5287	-959	15.3	0.0021	14.6	52.2	0	8.6	186
IS3	135	12940	51361	10.49	0.0024	0.0081	0.0119	4330	891	15.1	0.0018	14.7	54.4	0	7.5	195
IS4	142	13969	45972	9.69	0.0021	0.0071	0.0104	3751	2430	15.6	0.0017	15.5	58.7	0	6.9	210
IS5	153	15271	42847	9.31	0.0020	0.0065	0.0095	3378	3805	16.5	0.0017	16.6	64.1	0	6.7	230
IS6	167	16765	41242	9.22	0.0019	0.0061	0.0090	3144	5077	17.6	0.0017	18.0	70.3	0	6.7	253
IS7	181	18343	40165	9.23	0.0018	0.0058	0.0086	2957	6324	18.9	0.0017	19.4	76.9	0	6.7	276
IS8	196	20060	40112	9.43	0.0018	0.0057	0.0084	2862	7507	20.4	0.0018	21.1	84.0	0	6.9	302
IS9	213	21832	40338	9.69	0.0018	0.0056	0.0083	2792	8686	22.0	0.0019	22.8	91.4	0	7.1	329
IS10	229	23662	40844	10.00	0.0018	0.0056	0.0083	2746	9860	23.6	0.0019	24.6	99.0	0	7.3	357

1=Acidification, Mole H+ eq., 2=Climate change, kg CO2 eq., 3=Freshwater ecotoxicity, CTUe, 4=Freshwater eutrophication, kg P eq., 5=Human toxicity - carcinogenics, CTUh, 6=Human toxicity - non-carcinogenics, CTUh, 7=Ionizing radiation - ecosystems, CTUe, 8=Ionizing radiaton - human health, kg U235 eq., 9=Land use, kg SOC, 10=Marine eutrophication, kg N eq., 11=Ozone depletion, kg CFC-11 eq., 12=Particulate matter/Respiratory inorganics, kg PM2.5 eq., 13=Photochemical ozone formation, kg C2H4 eq., 14=Resource depletion - mineral, fossils and renewables, kg Sb eq., 15=Resource depletion - water, m3, 16=Terrestrial eutrophication, Mole N eq.

I.
ReCiPe Midpoint (H)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IS1	2160	13463	3477	860	15.5	28451	7151	845	5.82	9914	3.65	0.0028	49.5	56.6	110	3.01	287	217645
IS2	2015	12954	3327	649	12.1	21428	5300	636	4.87	7253	3.77	0.0022	44.4	54.0	102	2.40	252	162789
IS3	2059	13558	3467	543	10.5	17886	4340	530	4.53	5846	4.13	0.0020	44.0	56.3	103	2.12	246	134782
IS4	2186	14656	3736	481	9.7	15825	3760	469	4.46	4971	4.61	0.0018	45.6	60.6	109	2.00	252	118181
IS5	2361	16038	4079	444	9.3	14575	3387	432	4.54	4386	5.16	0.0018	48.4	66.1	118	1.96	264	107829
IS6	2568	17620	4474	423	9.2	13869	3152	410	4.72	3995	5.75	0.0018	52.0	72.4	128	1.97	282	101663
IS7	2790	19289	4892	408	9.2	13350	2964	395	4.94	3670	6.37	0.0018	55.9	79.1	139	2.00	301	96932
IS8	3036	21102	5347	404	9.5	13197	2870	390	5.23	3474	7.02	0.0019	60.3	86.4	151	2.07	324	95012
IS9	3290	22974	5817	403	9.7	13143	2799	388	5.54	3312	7.69	0.0019	65.0	94.0	163	2.16	347	93839
IS10	3554	24905	6302	405	10.0	13187	2753	389	5.87	3183	8.38	0.0020	69.9	101.8	176	2.25	372	93414

1=Agricultural land occupation, m2*a, 2=Climate Change, kg CO2 eq, 3=Fossil depletion, kg oil eq, 4=Freshwater ecotoxicity, kg 1,4-DB eq, 5=Freshwater eutrophication, kg P eq, 6=Human toxicity, kg 1,4-DB eq, 7=Ionising radiation, kg U235 eq, 8=Marine ecotoxicity, kg 1,4-DB eq, 9=Marine eutrophication, kg N eq, 10=Metal depletion, kg Fe eq, 11=Natural land transformation, m2, 12=Ozone depletion, kg CFC-11 eq, 13=Particulate matter formation, kg PM10 eq, 14=Photochemical oxidant formation, kg NMVOC, 15=Terrestrial acidification, kg SO2 eq, 16=Terrestrial ecotoxicity, kg 1,4-DB eq, 17=Urban land occupation, m2*a, 18=Water depletion, m3

2015 Wind Scenario Detailed LCA results

Table SI II.3A-I: detailed LCA results of IS 1-10 with Wind energy scenario for ReCiPe endpoint, ILCD-TOPSIS single score, ILCD Midpoint, and ReCiPe midpoint

A.
ReCiPe (H)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0086	165.8	2.744	50579
IS2	0.0098	161.0	2.445	49050
IS3	0.0114	169.6	2.410	51612
IS4	0.0132	184.2	2.490	56002
IS5	0.0151	202.1	2.634	61441
IS6	0.0172	222.6	2.823	67621
IS7	0.0192	244.0	3.030	74127
IS8	0.0214	267.3	3.269	81169
IS9	0.0236	291.2	3.518	88433
IS10	0.0258	315.9	3.779	95922

B.
ReCiPe (I)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0083	131.7	1.758	72795
IS2	0.0093	132.4	1.432	73126
IS3	0.0107	142.9	1.300	78859
IS4	0.0123	157.8	1.251	87035
IS5	0.0141	175.2	1.249	96630
IS6	0.0159	194.5	1.279	107238
IS7	0.0178	214.6	1.320	118316
IS8	0.0198	236.1	1.382	130136
IS9	0.0218	258.2	1.451	142288
IS10	0.0239	280.8	1.526	154776

C.
ReCiPe (E)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0259	1421.1	2.744	426893
IS2	0.0247	1249.9	2.445	375472
IS3	0.0257	1218.0	2.410	365901
IS4	0.0276	1246.8	2.490	374555
IS5	0.0301	1309.6	2.634	393436
IS6	0.0330	1395.9	2.823	419359
IS7	0.0361	1491.5	3.030	448063
IS8	0.0394	1603.4	3.269	481682
IS9	0.0429	1721.0	3.518	517012
IS10	0.0464	1844.3	3.779	554065

D.
ReCiPe (EW)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0086	165.8	2.744	56197
IS2	0.0098	161.0	2.445	54498
IS3	0.0114	169.6	2.410	57345
IS4	0.0132	184.2	2.490	62222
IS5	0.0151	202.1	2.634	68265
IS6	0.0172	222.6	2.823	75131
IS7	0.0192	244.0	3.030	82361
IS8	0.0214	267.3	3.269	90185
IS9	0.0236	291.2	3.518	98256
IS10	0.0258	315.9	3.779	106577

E.
ReCiPe (HH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0086	165.8	2.744	116501
IS2	0.0098	161.0	2.445	113096
IS3	0.0114	169.6	2.410	119094
IS4	0.0132	184.2	2.490	129291
IS5	0.0151	202.1	2.634	141902
IS6	0.0172	222.6	2.823	156215
IS7	0.0192	244.0	3.030	171282
IS8	0.0214	267.3	3.269	187580
IS9	0.0236	291.2	3.518	204391
IS10	0.0258	315.9	3.779	221721

F.
ReCiPe (EH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0086	165.8	2.744	25294
IS2	0.0098	161.0	2.445	24530
IS3	0.0114	169.6	2.410	25812
IS4	0.0132	184.2	2.490	28008
IS5	0.0151	202.1	2.634	30728
IS6	0.0172	222.6	2.823	33819
IS7	0.0192	244.0	3.030	37073
IS8	0.0214	267.3	3.269	40595
IS9	0.0236	291.2	3.518	44228
IS10	0.0258	315.9	3.779	47974

G.
ILCD-TOPSIS single score

	Hierarchist	Individualist	Egalitarian	Equal Weights	Human Health	Environmental Health
IS1	0.741	0.570	0.721	0.724	0.522	0.732
IS2	0.859	0.745	0.850	0.847	0.713	0.860
IS3	0.884	0.841	0.886	0.878	0.829	0.892
IS4	0.816	0.836	0.824	0.814	0.846	0.825
IS5	0.716	0.768	0.725	0.717	0.789	0.725
IS6	0.605	0.684	0.617	0.609	0.714	0.614
IS7	0.495	0.604	0.508	0.502	0.641	0.503
IS8	0.384	0.524	0.400	0.396	0.567	0.391
IS9	0.290	0.455	0.307	0.306	0.501	0.295
IS10	0.230	0.399	0.246	0.248	0.446	0.231

H.
ILCD Midpoint

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IS1	84	10537	48571	5.08	0.0030	0.0044	0.0020	581	6337	11.5	0.0007	10.8	40.5	0.002	2.9	136
IS2	90	10682	38218	4.61	0.0023	0.0035	0.0020	575	6167	11.2	0.0007	10.9	42.1	0.003	2.8	145
IS3	101	11594	33495	4.61	0.0020	0.0032	0.0022	615	6510	11.9	0.0008	11.8	46.5	0.003	2.9	162
IS4	115	12854	31179	4.82	0.0018	0.0030	0.0024	674	7082	12.9	0.0008	13.1	52.1	0.003	3.2	184
IS5	130	14317	30190	5.15	0.0017	0.0030	0.0026	746	7786	14.2	0.0009	14.5	58.5	0.004	3.5	207
IS6	146	15925	30095	5.55	0.0016	0.0030	0.0029	826	8583	15.6	0.0010	16.1	65.3	0.004	3.8	232
IS7	162	17602	30320	5.99	0.0016	0.0031	0.0032	909	9420	17.2	0.0011	17.8	72.5	0.005	4.2	259
IS8	179	19385	31153	6.48	0.0016	0.0032	0.0035	999	10325	18.8	0.0013	19.6	80.0	0.005	4.6	286
IS9	197	21216	32160	7.00	0.0016	0.0034	0.0038	1091	11258	20.5	0.0014	21.5	87.8	0.006	5.0	314
IS10	215	23097	33343	7.54	0.0016	0.0035	0.0042	1186	12219	22.2	0.0015	23.3	95.7	0.007	5.4	343

1=Acidification, Mole H+ eq., 2=Climate change, kg CO2 eq., 3=Freshwater ecotoxicity, CTUe, 4=Freshwater eutrophication, kg P eq., 5=Human toxicity - carcinogenics, CTUh, 6=Human toxicity - non-carcinogenics, CTUh, 7=Ionizing radiation - ecosystems, CTUe, 8=Ionizing radiaton - human health, kg U235 eq., 9=Land use, kg SOC, 10=Marine eutrophication, kg N eq., 11=Ozone depletion, kg CFC-11 eq., 12=Particulate matter/Respiratory inorganics, kg PM2.5 eq., 13=Photochemical ozone formation, kg C2H4 eq., 14=Resource depletion - mineral, fossils and renewables, kg Sb eq., 15=Resource depletion - water, m3, 16=Terrestrial eutrophication, Mole N eq.

ReCiPe Midpoint (H)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IS1	942	10819	2676	1904	5.1	9048	582	1681	3.28	5655	2.52	0.0008	32.7	42.5	64	1.14	145	48598
IS2	1139	11053	2751	1400	4.6	7477	577	1237	3.04	4191	2.95	0.0008	32.3	43.9	69	1.05	150	41243
IS3	1368	12059	3013	1135	4.6	6886	616	1004	3.09	3431	3.49	0.0008	34.5	48.3	78	1.06	165	38942
IS4	1614	13415	3360	971	4.8	6717	676	861	3.27	2971	4.08	0.0009	37.7	54.0	88	1.12	185	38827
IS5	1872	14977	3758	863	5.2	6782	748	767	3.52	2675	4.70	0.0010	41.6	60.4	100	1.20	207	39931
IS6	2138	16685	4191	792	5.6	7006	828	706	3.82	2489	5.35	0.0011	46.0	67.4	112	1.31	232	41868
IS7	2410	18463	4642	734	6.0	7289	912	656	4.15	2339	6.01	0.0012	50.6	74.7	125	1.42	257	44122
IS8	2690	20350	5119	701	6.5	7681	1002	628	4.51	2263	6.70	0.0013	55.6	82.4	138	1.54	283	46952
IS9	2974	22288	5609	674	7.0	8108	1095	605	4.88	2207	7.40	0.0014	60.6	90.4	152	1.67	311	49971
IS10	3264	24275	6111	653	7.6	8569	1190	588	5.27	2169	8.11	0.0015	65.9	98.5	166	1.80	339	53178

1=Agricultural land occupation, m2*a, 2=Climate Change, kg CO2 eq, 3=Fossil depletion, kg oil eq, 4=Freshwater ecotoxicity, kg 1,4-DB eq, 5=Freshwater eutrophication, kg P eq, 6=Human toxicity, kg 1,4-DB eq, 7=Ionising radiation, kg U235 eq, 8=Marine ecotoxicity, kg 1,4-DB eq, 9=Marine eutrophication, kg N eq, 10=Metal depletion, kg Fe eq, 11=Natural land transformation, m2, 12=Ozone depletion, kg CFC-11 eq, 13=Particulate matter formation, kg PM10 eq, 14=Photochemical oxidant formation, kg NMVOC, 15=Terrestrial acidification, kg SO2 eq, 16=Terrestrial ecotoxicity, kg 1,4-DB eq, 17=Urban land occupation, m2*a, 18=Water depletion, m3

2015 Hydro Detailed LCA results

Table SI II.4A-I: detailed LCA results of Hydro energy scenario for ReCiPe endpoint, ILCD-TOPSIS single score, ILCD Midpoint, and ReCiPe midpoint

A.
ReCiPe (H)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0164	226.2	1.149	68220
IS2	0.0154	204.5	1.298	61734
IS3	0.0158	203.9	1.505	61614
IS4	0.0169	212.5	1.741	64283
IS5	0.0183	226.4	1.993	68527
IS6	0.0199	243.9	2.259	73861
IS7	0.0217	262.9	2.532	79639
IS8	0.0236	284.4	2.815	86185
IS9	0.0256	306.9	3.104	93011
IS10	0.0277	330.3	3.399	100121

B.
ReCiPe (I)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0169	219.2	0.523	120691
IS2	0.0155	195.4	0.543	107564
IS3	0.0156	192.5	0.599	106014
IS4	0.0164	198.9	0.671	109519
IS5	0.0175	210.4	0.753	115868
IS6	0.0190	225.5	0.842	124180
IS7	0.0205	242.0	0.934	133278
IS8	0.0223	261.0	1.031	143753
IS9	0.0241	280.9	1.130	154718
IS10	0.0260	301.7	1.232	166176

C.
ReCiPe (E)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.3522	833.8	1.149	250535
IS2	0.2593	827.6	1.298	248667
IS3	0.2107	885.0	1.505	265914
IS4	0.1808	971.1	1.741	291767
IS5	0.1612	1073.7	1.993	322602
IS6	0.1485	1188.2	2.259	356979
IS7	0.1380	1308.0	2.532	392969
IS8	0.1322	1436.4	2.815	431544
IS9	0.1275	1568.5	3.104	471247
IS10	0.1241	1704.5	3.399	512089

D.
ReCiPe (EW)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0164	226.2	1.149	75798
IS2	0.0154	204.5	1.298	68591
IS3	0.0158	203.9	1.505	68458
IS4	0.0169	212.5	1.741	71423
IS5	0.0183	226.4	1.993	76138
IS6	0.0199	243.9	2.259	82065
IS7	0.0217	262.9	2.532	88484
IS8	0.0236	284.4	2.815	95757
IS9	0.0256	306.9	3.104	103342
IS10	0.0277	330.3	3.399	111242

E.
ReCiPe (HH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0164	226.2	1.149	158536
IS2	0.0154	204.5	1.298	143320
IS3	0.0158	203.9	1.505	142926
IS4	0.0169	212.5	1.741	149024
IS5	0.0183	226.4	1.993	158785
IS6	0.0199	243.9	2.259	171084
IS7	0.0217	262.9	2.532	184414
IS8	0.0236	284.4	2.815	199531
IS9	0.0256	306.9	3.104	215299
IS10	0.0277	330.3	3.399	231726

F.
ReCiPe (EH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0164	226.2	1.149	34118
IS2	0.0154	204.5	1.298	30875
IS3	0.0158	203.9	1.505	30815
IS4	0.0169	212.5	1.741	32150
IS5	0.0183	226.4	1.993	34272
IS6	0.0199	243.9	2.259	36940
IS7	0.0217	262.9	2.532	39830
IS8	0.0236	284.4	2.815	43104
IS9	0.0256	306.9	3.104	46519
IS10	0.0277	330.3	3.399	50075

G.
ILCD-TOPSIS single score

	Hierarchist	Individualist	Egalitarian	Equal Weights	Human Health	Environmental Health
IS1	0.986	0.965	0.986	0.983	0.960	0.990
IS2	0.837	0.881	0.869	0.848	0.900	0.895
IS3	0.731	0.791	0.773	0.745	0.816	0.804
IS4	0.636	0.699	0.678	0.650	0.725	0.707
IS5	0.541	0.600	0.578	0.554	0.623	0.603
IS6	0.443	0.492	0.473	0.453	0.511	0.492
IS7	0.339	0.378	0.362	0.347	0.393	0.376
IS8	0.231	0.257	0.246	0.236	0.266	0.254
IS9	0.117	0.131	0.125	0.120	0.135	0.129
IS10	0.000	0.000	0.000	0.000	0.000	0.000

H.
ILCD Midpoint

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IS1	57	9083	12188	2.13	0.0007	0.0011	0.0015	408	-143416	7.3	0.0005	7.3	29.2	0.002	1.7	103
IS2	71	9636	12058	2.49	0.0006	0.0012	0.0016	451	-101507	8.2	0.0005	8.4	34.0	0.002	2.0	121
IS3	86	10769	12868	2.94	0.0006	0.0013	0.0018	517	-78391	9.5	0.0006	9.8	40.1	0.003	2.3	143
IS4	102	12171	14100	3.44	0.0007	0.0015	0.0021	594	-63215	10.9	0.0007	11.4	46.8	0.003	2.6	168
IS5	119	13733	15576	3.96	0.0007	0.0017	0.0024	677	-52363	12.5	0.0008	13.1	53.9	0.004	3.0	194
IS6	136	15411	17226	4.51	0.0008	0.0019	0.0027	765	-44388	14.1	0.0009	14.9	61.3	0.004	3.4	221
IS7	154	17147	18955	5.07	0.0008	0.0021	0.0030	856	-37362	15.8	0.0011	16.7	69.0	0.005	3.8	248
IS8	172	18971	20809	5.64	0.0009	0.0023	0.0033	950	-32249	17.6	0.0012	18.6	76.8	0.005	4.3	277
IS9	190	20839	22719	6.23	0.0010	0.0025	0.0037	1047	-27604	19.4	0.0013	20.6	84.8	0.006	4.7	305
IS10	209	22750	24683	6.83	0.0010	0.0027	0.0040	1145	-23425	21.2	0.0014	22.5	93.0	0.006	5.1	335

1=Acidification, Mole H+ eq., 2=Climate change, kg CO2 eq., 3=Freshwater ecotoxicity, CTUe, 4=Freshwater eutrophication, kg P eq., 5=Human toxicity - carcinogenics, CTUh, 6=Human toxicity - non-carcinogenics, CTUh, 7=Ionizing radiation - ecosystems, CTUe, 8=Ionizing radiaton - human health, kg U235 eq., 9=Land use, kg SOC, 10=Marine eutrophication, kg N eq., 11=Ozone depletion, kg CFC-11 eq., 12=Particulate matter/Respiratory inorganics, kg PM2.5 eq., 13=Photochemical ozone formation, kg C2H4 eq., 14=Resource depletion - mineral, fossils and renewables, kg Sb eq., 15=Resource depletion - water, m3, 16=Terrestrial eutrophication, Mole N eq.

I.
ReCiPe Midpoint (H)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IS1	777	23867	1699	378	2.1	2633	409	335	1.46	1028	36.68	0.0005	21.7	30.0	44	0.55	106	3082050
IS2	1020	20435	2048	302	2.5	2865	452	270	1.73	864	27.51	0.0005	24.4	34.9	54	0.63	122	2222320
IS3	1274	19456	2459	269	3.0	3250	518	242	2.06	808	22.85	0.0006	28.2	41.2	66	0.73	143	1758730
IS4	1537	19540	2901	255	3.4	3706	595	230	2.41	800	20.11	0.0007	32.6	48.1	78	0.84	167	1462800
IS5	1805	20217	3365	250	4.0	4205	679	227	2.79	817	18.42	0.0008	37.2	55.4	91	0.97	192	1258330
IS6	2079	21300	3845	252	4.5	4737	767	230	3.18	852	17.43	0.0010	42.1	63.0	105	1.10	218	1114860
IS7	2358	22539	4336	257	5.1	5285	858	236	3.58	894	16.69	0.0011	47.2	70.8	118	1.23	245	991763
IS8	2642	24060	4841	267	5.7	5858	953	245	3.99	948	16.41	0.0012	52.4	78.9	132	1.37	272	909355
IS9	2931	25674	5355	278	6.3	6443	1050	256	4.41	1006	16.26	0.0013	57.8	87.1	146	1.52	300	837164
IS10	3225	27381	5879	290	6.9	7042	1149	268	4.84	1068	16.24	0.0015	63.2	95.5	161	1.66	329	775190

1=Agricultural land occupation, m2*a, 2=Climate Change, kg CO2 eq, 3=Fossil depletion, kg oil eq, 4=Freshwater ecotoxicity, kg 1,4-DB eq, 5=Freshwater eutrophication, kg P eq, 6=Human toxicity, kg 1,4-DB eq, 7=Ionising radiation, kg U235 eq, 8=Marine ecotoxicity, kg 1,4-DB eq, 9=Marine eutrophication, kg N eq, 10=Metal depletion, kg Fe eq, 11=Natural land transformation, m2, 12=Ozone depletion, kg CFC-11 eq, 13=Particulate matter formation, kg PM10 eq, 14=Photochemical oxidant formation, kg NMVOC, 15=Terrestrial acidification, kg SO2 eq, 16=Terrestrial ecotoxicity, kg 1,4-DB eq, 17=Urban land occupation, m2*a, 18=Water depletion, m3

2015 Nuclear Detailed LCA results

Table SI II.5A-I: detailed LCA results of Nuclear energy scenario for ReCiPe endpoint, ILCD-TOPSIS single score, ILCD Midpoint, and ReCiPe midpoint

A.
ReCiPe (H)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0080	199.9	1.825	60523
IS2	0.0093	185.5	1.784	56200
IS3	0.0110	188.9	1.889	57250
IS4	0.0129	200.2	2.058	60670
IS5	0.0149	215.8	2.265	65435
IS6	0.0169	234.6	2.498	71138
IS7	0.0190	254.7	2.743	77234
IS8	0.0212	277.0	3.007	83996
IS9	0.0234	300.1	3.279	91014
IS10	0.0257	324.0	3.560	98289

B.
ReCiPe (I)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0075	146.3	0.933	80676
IS2	0.0087	142.9	0.838	78792
IS3	0.0103	151.2	0.831	83327
IS4	0.0120	164.7	0.864	90734
IS5	0.0138	181.1	0.918	99795
IS6	0.0157	199.7	0.987	110026
IS7	0.0176	219.2	1.062	120778
IS8	0.0196	240.3	1.147	132377
IS9	0.0217	262.0	1.237	144333
IS10	0.0237	284.3	1.330	156652

C.
ReCiPe (E)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0196	2512.7	1.825	754171
IS2	0.0202	2034.7	1.784	610788
IS3	0.0221	1836.9	1.889	551449
IS4	0.0247	1759.2	2.058	528185
IS5	0.0276	1748.1	2.265	524890
IS6	0.0308	1782.0	2.498	535124
IS7	0.0341	1832.5	2.743	550304
IS8	0.0376	1913.7	3.007	574727
IS9	0.0412	2004.2	3.279	601943
IS10	0.0449	2104.1	3.560	631962

D.
ReCiPe (EW)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0080	199.9	1.825	67247
IS2	0.0093	185.5	1.784	62443
IS3	0.0110	188.9	1.889	63610
IS4	0.0129	200.2	2.058	67409
IS5	0.0149	215.8	2.265	72703
IS6	0.0169	234.6	2.498	79040
IS7	0.0190	254.7	2.743	85813
IS8	0.0212	277.0	3.007	93326
IS9	0.0234	300.1	3.279	101123
IS10	0.0257	324.0	3.560	109207

E.
ReCiPe (HH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0080	199.9	1.825	140211
IS2	0.0093	185.5	1.784	130144
IS3	0.0110	188.9	1.889	132537
IS4	0.0129	200.2	2.058	140421
IS5	0.0149	215.8	2.265	151425
IS6	0.0169	234.6	2.498	164602
IS7	0.0190	254.7	2.743	178689
IS8	0.0212	277.0	3.007	194321
IS9	0.0234	300.1	3.279	210544
IS10	0.0257	324.0	3.560	227364

F.
ReCiPe (EH)

	Ecosystems-total	Human Health-total	Resources-total	Single Score
IS1	0.0080	199.9	1.825	30266
IS2	0.0093	185.5	1.784	28105
IS3	0.0110	188.9	1.889	28631
IS4	0.0129	200.2	2.058	30341
IS5	0.0149	215.8	2.265	32725
IS6	0.0169	234.6	2.498	35578
IS7	0.0190	254.7	2.743	38626
IS8	0.0212	277.0	3.007	42009
IS9	0.0234	300.1	3.279	45519
IS10	0.0257	324.0	3.560	49158

G.
ILCD-TOPSIS single score

	Hierarchist	Individualist	Egalitarian	Equal Weights	Human Health	Environmental Health
IS1	0.437	0.301	0.439	0.430	0.239	0.455
IS2	0.581	0.489	0.585	0.575	0.457	0.598
IS3	0.684	0.641	0.688	0.680	0.628	0.695
IS4	0.738	0.735	0.741	0.736	0.735	0.742
IS5	0.743	0.782	0.745	0.743	0.796	0.740
IS6	0.712	0.788	0.712	0.714	0.817	0.702
IS7	0.671	0.773	0.669	0.675	0.815	0.656
IS8	0.625	0.743	0.622	0.632	0.792	0.606
IS9	0.585	0.712	0.580	0.592	0.765	0.562
IS10	0.550	0.682	0.544	0.558	0.737	0.526

H.
ILCD Midpoint

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IS1	75	9296	34141	4.65	0.0012	0.0102	0.5358	256674	7096	25.9	0.0393	12.9	38.2	0.002	506.7	137
IS2	84	9789	27842	4.30	0.0010	0.0077	0.3858	184708	6713	21.5	0.0285	12.4	40.5	0.002	365.0	146
IS3	96	10890	25314	4.37	0.0009	0.0064	0.3048	145805	6941	20.0	0.0226	13.0	45.2	0.003	288.5	163
IS4	111	12272	24405	4.62	0.0009	0.0057	0.2529	120890	7439	19.6	0.0190	14.1	51.0	0.003	239.7	184
IS5	126	13819	24394	4.97	0.0009	0.0053	0.2170	103607	8091	19.9	0.0164	15.4	57.5	0.004	205.8	207
IS6	143	15486	24991	5.40	0.0009	0.0051	0.1917	91411	8851	20.7	0.0147	16.9	64.5	0.004	182.0	233
IS7	160	17214	25813	5.85	0.0010	0.0049	0.1699	80912	9657	21.6	0.0132	18.5	71.8	0.005	161.6	259
IS8	177	19032	27050	6.36	0.0010	0.0049	0.1552	73806	10541	22.9	0.0122	20.2	79.4	0.005	147.8	286
IS9	195	20894	28416	6.89	0.0011	0.0049	0.1423	67549	11455	24.2	0.0114	22.0	87.2	0.006	135.7	314
IS10	213	22801	29909	7.43	0.0012	0.0049	0.1312	62141	12400	25.7	0.0107	23.9	95.1	0.006	125.3	343

1=Acidification, Mole H+ eq., 2=Climate change, kg CO2 eq., 3=Freshwater ecotoxicity, CTUe, 4=Freshwater eutrophication, kg P eq., 5=Human toxicity - carcinogenics, CTUh, 6=Human toxicity - non-carcinogenics, CTUh, 7=Ionizing radiation - ecosystems, CTUe, 8=Ionizing radiaton - human health, kg U235 eq., 9=Land use, kg SOC, 10=Marine eutrophication, kg N eq., 11=Ozone depletion, kg CFC-11 eq., 12=Particulate matter/Respiratory inorganics, kg PM2.5 eq., 13=Photochemical ozone formation, kg C2H4 eq., 14=Resource depletion - mineral, fossils and renewables, kg Sb eq., 15=Resource depletion - water, m3, 16=Terrestrial eutrophication, Mole N eq.

I.

ReCiPe Midpoint (H)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IS1	964	9610	2422	229	4.7	12294	257446	238	17.76	2274	2.46	0.0393	37.7	39.2	58	1.56	142	80510
IS2	1155	10184	2568	195	4.3	9811	185264	200	13.45	1760	2.91	0.0285	35.9	41.5	64	1.35	148	64188
IS3	1381	11373	2869	185	4.4	8727	146243	187	11.30	1515	3.45	0.0226	37.3	46.4	74	1.30	163	57034
IS4	1625	12848	3241	185	4.6	8241	121254	184	10.06	1385	4.05	0.0190	40.1	52.4	85	1.32	183	53807
IS5	1880	14491	3655	190	5.0	8085	103918	188	9.34	1317	4.67	0.0164	43.7	59.1	97	1.38	206	52748
IS6	2146	16257	4101	200	5.4	8154	91686	196	8.94	1293	5.33	0.0147	47.8	66.3	110	1.46	230	53156
IS7	2417	18086	4562	211	5.9	8303	81156	205	8.67	1283	5.99	0.0132	52.2	73.7	123	1.55	256	54091
IS8	2696	20007	5047	225	6.4	8604	74028	217	8.62	1302	6.68	0.0122	57.0	81.5	136	1.66	282	56025
IS9	2980	21974	5543	239	6.9	8950	67752	231	8.64	1329	7.38	0.0114	61.9	89.5	150	1.78	310	58252
IS10	3269	23988	6051	255	7.5	9342	62328	245	8.71	1365	8.10	0.0107	67.1	97.7	164	1.90	338	60774

1=Agricultural land occupation, m2*a, 2=Climate Change, kg CO2 eq, 3=Fossil depletion, kg oil eq, 4=Freshwater ecotoxicity, kg 1,4-DB eq, 5=Freshwater eutrophication, kg P eq, 6=Human toxicity, kg 1,4-DB eq, 7=Ionising radiation, kg U235 eq, 8=Marine ecotoxicity, kg 1,4-DB eq, 9=Marine eutrophication, kg N eq, 10=Metal depletion, kg Fe eq, 11=Natural land transformation, m2, 12=Ozone depletion, kg CFC-11 eq, 13=Particulate matter formation, kg PM10 eq, 14=Photochemical oxidant formation, kg NMVOC, 15=Terrestrial acidification, kg SO2 eq, 16=Terrestrial ecotoxicity, kg 1,4-DB eq, 17=Urban land occupation, m2*a, 18=Water depletion, m3